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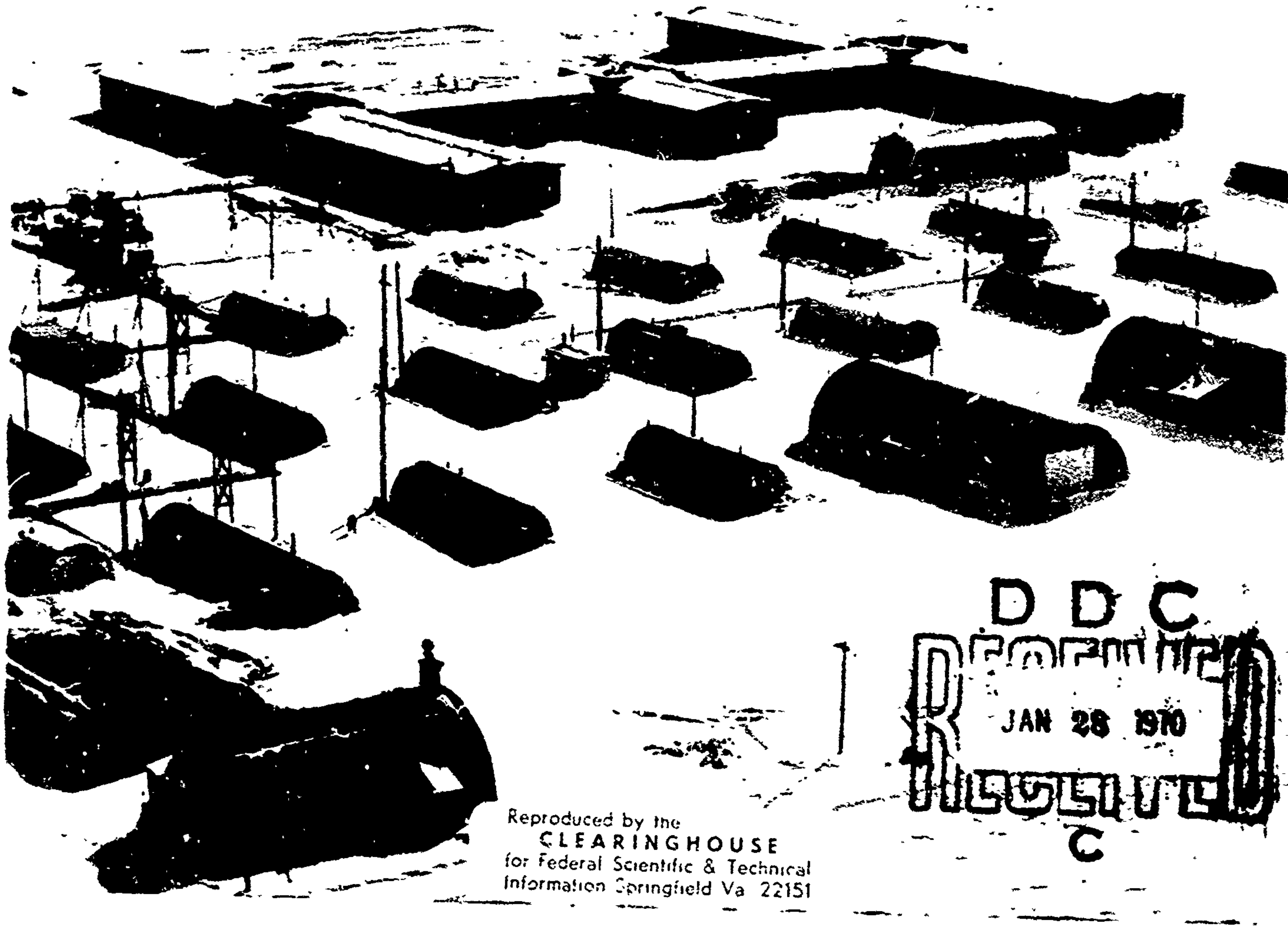

JOURNAL OF THE ARCTIC INSTITUTE OF NORTH AMERICA

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Edited by

A. P. B. Monson and J. E. Saier

ARCTIC

Journal of the Arctic Institute of North America

EDITOR, A. P. B. MONSON

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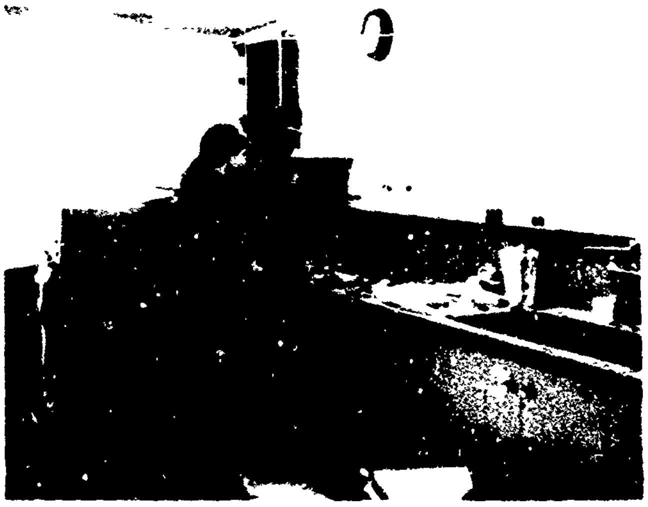

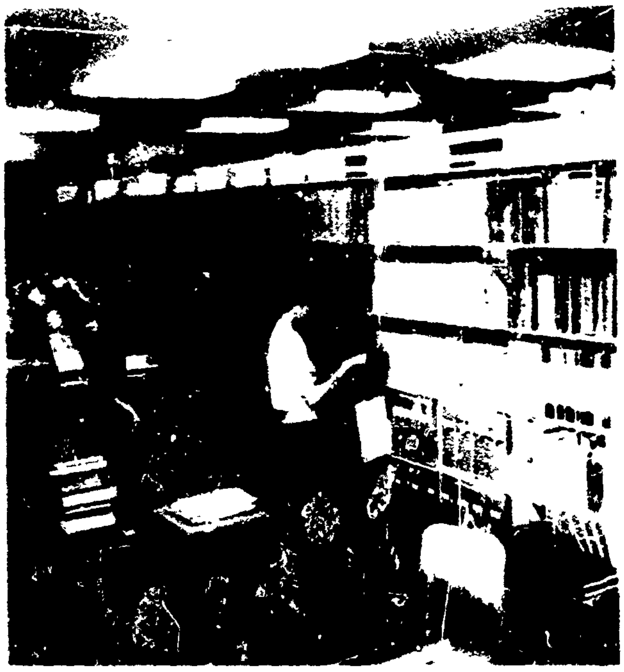

Top: *Max C. Brewer, Director of the Naval Arctic Research Laboratory; John F. Schindler, Assistant Director; Susan Kaplan, Kenny Toovak.* Centre: *Johnu Dickerson; Winston Yellar.* Bottom: *David Norton, Merle Solomon.*

Foreword

Interest in northern Alaska and its arctic waters was first shown by the U.S. Navy late in the nineteenth century. However, it was not until 1923 that this interest materialized with the establishment of Naval Petroleum Reserve No. 4. Extensive exploration began there in 1944, and by 1947 the ground was prepared for the two-year-old Office of Naval Research (ONR) to initiate the Arctic Research Laboratory operations at the Barrow base camp; twenty-two years later the new Naval Arctic Research Laboratory (NARL) was opened.

The Office of Naval Research had sought the advice of the equally young Arctic Institute of North America (AINA), among others, concerning the proposal to establish the Laboratory. Since that time ONR, NARL and AINA have been closely associated in numerous projects and programs and, in fact, the Symposium held in connection with the dedication of the new Laboratory in 1969 was co-sponsored by the Institute, ONR and the University of Alaska.

For these reasons it was considered appropriate to publish in *Arctic* the papers emanating from that Symposium; thus this September issue contains a series of substantial statements giving the major scientific accomplishments in the principal fields of NARL-based studies to date, with predictions and recommendations for the next twenty years of research.

Avant-Propos

La Marine des Etats-Unis s'est d'abord intéressée au nord de l'Alaska et à ses eaux arctiques vers la fin du siècle dernier. Cependant, ce n'est qu'en 1923 que cet intérêt s'est matérialisé par l'établissement de la *Naval Petroleum Reserve No. 4*. L'exploration intensive y débuta en 1944 : vers 1947, l'*Office of Naval Research* (ONR), vieux de deux ans, pouvait lancer les opérations de l'*Arctic Research Laboratory* au camp de base de Barrow ; vingt-deux ans plus tard, on inaugura le nouveau *Naval Arctic Research Laboratory.*

L'*Office of Naval Research* avait sollicité l'avis, entre autres, du jeune *Arctic Institute of North America* (AINA) sur son projet d'établir le laboratoire. Depuis cette époque, l'ONR, le NARL et l'AINA ont été intimement associés dans de nombreux projets et programmes de recherches ; de fait, le symposium tenu à l'occasion de l'inauguration du nouveau laboratoire en 1969 était commandité conjointement par l'AINA, l'ONR et l'université d'Alaska.

Pour ces raisons, il a semblé approprié de publier dans *Arctic* les communications présentées au Symposium ; c'est ainsi que cette livraison de septembre contient une série d'exposés substantiels sur les réalisations scientifiques majeures du NARL dans ses principaux domaines de recherches, ainsi que des prévisions et des recommandations pour les vingt prochaines années.

Предисловие

Впервые американский военно-морской флот проявил интерес к северной Аляске и омывающим ее полярным морям в конце прошлого столетия. Однако этот интерес принял более конкретные формы лишь в 1923 г., когда была обоснована топливная база Naval Petroleum Reserve No. 4. Интенсивные разведочные работы были начаты в 1944 г. В 1947 г. Научно-исследовательское управление военно-морского флота (ОНР) обосновало в лагере Барроу Полярный научно-исследовательский институт. Спустя двадцать два года был открыт новый Полярный научно-исследовательский институт военно-морского флота (НАРЛ.)

Научно-исследовательское управление неоднократно обращалось за советом к Полярному институту Северной Америки (АИНА), в том числе по вопросам, касающимся открытия нового института. ОНР, НАРЛ и АИНА разработали много совместных проектов. Совещание, проведенное в связи с открытием института, было организовано совместными усилиями АИНА, ОНР и Университета Аляски.

В связи с этим было решено опубликовать в журнале *Arctic* доклады, прочитанные на Совещании. В настоящем номере журнала обсуждаются наиболее важные результаты исследований, проведенных под руководством НАРЛ по сегодняшний день, а также перспективные направления научно-исследовательской работы и рекомендации на ближайшие двадцать лет.

Introduction

T. B. OWEN[1]

The Office of Naval Research was charged by the Congress in 1946 with two principal missions: first, the encouragement, planning, promotion, initiation and co-ordination of a program of naval research and, second, the conduct of a research program to augment those conducted by other elements of the Navy. I have characterized the first of these two charges as responsibility for conducting a program of research of opportunity; the second as a program of research of response. By opportunity is meant that we survey the various disciplines of science and attempt to sponsor and encourage research in those that offer promise not only to the Navy, but to other components of the economy as well. The research of response relates to problems arising in development, the solutions to which can only be provided by research. I think we can summarize our responsibilities as an office as being those of providing knowledge and stimulating appreciation.

The Symposium was held in recognition of the construction and dedication of a new facility at the Naval Arctic Research Laboratory at Barrow, Alaska. The Office of Naval Research undertook to support such a laboratory in 1947. In 1954, responsibility for the management and operation of the laboratory was undertaken by the University of Alaska and we are indeed grateful for the support given us at that time by Dr. Ernest Patty, President emeritus, and, of course, more recently by President Wood and the staff and faculty of the University. I would like also to acknowledge the former directors of the laboratory and their wives; their roles in furthering NARL's development are described in "The Story of the Naval Arctic Research Laboratory" which follows these introductory remarks. I certainly want also to express our thanks for the support given us by the Alaskan Command and elements thereof.

The papers presented at the Symposium and published herein cover a spectrum of arctic research involving the terrestrial, the marine and the atmospheric sciences. I think that in these we see the responsibilities of my office being discharged by providing knowledge and, certainly at the laboratory, by applying that knowledge. We hope we are only on the first step of a major program of construction at Barrow so that we can continue to serve and give additional assistance to investigators who want so badly to do work in that very important region.

In the circumstances it is very fitting that we were one of the co-sponsors of this Symposium, and on behalf of the Office of Naval Research and of all the participants at the Symposium I would like to express warm thanks to our host campus, the University of Alaska. We certainly appreciate the cooperation and support that this wonderful institution has given us over a period of years. I think

[1]Rear Admiral, U.S.N., Chief of Naval Research, Office of Naval Research, Washington, D.C.

this is a tribute to the leadership of Dr. Wood and his predecessors and to the support given to the University by the Board of Regents, the Governors, and by the State Legislature. I would like to thank The Arctic Institute of North America for the continuing interest it has had in working with the Office of Naval Research in the program of arctic environmental research, and more particularly for the excellent arrangements that were made in connection with this Symposium.

I think that I can summarize my feelings by saying that it is a real privilege as Chief of Naval Research to participate in a cooperative program of arctic research in an environment that is so important to Alaska and to the nation with its benefits to our society, our economy and our national security.

The Story of the Naval Arctic Research Laboratory

JOHN C. REED[1]

It was 6 August 1947 — a heavily laden C-46 lumbered over the pierced-metal surface laid on the coarse beach sand and rolled to a stop. Out from the load of freight climbed seven men led by Professor Laurence Irving of Swarthmore College. The sun was still high, for the days were long, it being only about six weeks past the twenty-first of June, and even at midnight the sun was just beginning to touch the northern horizon. For a change the sky was clear, the wind calm, and the sea was free of ice as far as the eye could see. The dull greenish-brown tundra relieved by the myriad of lakes, large and small, stretched southward seemingly without limit toward the Brooks Range over which the aircraft had come. Thus the Arctic welcomed to Point Barrow the first group of scientists that formed the nucleus of what was to become the Arctic Research Laboratory, and later (1967) the Naval Arctic Research Laboratory (NARL) of the Office of Naval Research.

It was a historic occasion, although the little group sweltering in unfamiliar Navy-issued cold-weather clothing did not realize it as they gazed around at the strange environment. The temperature was in the fifties and all around were the noise and hustle of an oil-exploration camp. Tractors churned the soft sand as they hauled equipment to storage areas. Weasels, those small tracked vehicles, so useful in the Arctic, seemed to be scooting in all directions on a variety of missions. The landscape was dotted with fuel drums, that ubiquitous trade-mark of the American developer in out-of-the-way places all over the world. At the beach lay power barges ready for their mission of lightering freight ashore.

Not much attention was paid to the small group of scientists for this was the main supply camp of the Navy's exploration for oil in Naval Petroleum Reserve No. 4 — an operation known as Pet 4 that was in full swing in 1947, after three years of intense activity. The annual ship expedition, called BAREX for Barrow Expedition, was due and first attention was being given to preparations for unloading the ships and hastening them south before the polar ice pack again moved in to the shore.

Thus the Arctic Research Laboratory was launched without any special notice. That Laboratory for a generation has been the major centre for U.S. arctic research. It is the only U.S. laboratory devoted to fulltime support of basic research in the Arctic. From it has come a steady flow of arctic environmental knowledge that has repeatedly stood this nation in good stead. Dr. M. E. Britton at one time pointed out that "one distinguished Canadian has expressed the view that results from the research of a single permafrost program at the Arctic Research Laboratory enabled savings in the cost of construction of the Distant

[1]The Arctic Institute of North America, Washington, D.C.

Early Warning line greater than all the money spent on the ARL in its entire history."

As time went on the Laboratory was expanded and improved. Many of the organizational and administrative relationships changed and the course of NARL was altered in response to those changes. Some of the changes were unrelated to U.S. research patterns but nevertheless had a major influence on the Laboratory. Examples are the shutting down in 1953 of Pet 4, the oil exploration program, and the assumption of the operation of the facilities by Air Force contractors under Navy permit.

Other changes were intimately related to the progress of U. S. research in general. The Office of Naval Research was new — only about one and a half years old — when ARL came into being under its sponsorship. The Laboratory and the policies that were developed to guide it were important and influential in regard to ONR itself. The Arctic Institute of North America, only a few months older than ONR, has been closely associated with ARL from the start, and the influence has been great on both organizations. The National Science Foundation came into being by Act of Congress in 1950. At that time both ONR and ARL were active, productive organizations. During the early 1960's the NSF developed a large, balanced, integrated antarctic research program, but nothing comparable was achieved in the Arctic nor has yet been achieved. Some speculate that the Arctic was provided for sufficiently by the ONR through ARL. With the International Geophysical Year in 1957-1958 came a small arctic program. Projects under that program were assisted by ARL when they came within its support range.

Following World War II, the University of Alaska embarked on an accelerating course of growth and expansion in many ways; that trend continues under President William R. Wood. The Laboratory became specifically associated with the University of Alaska in 1954 when, under E.N. Patty, the University's third President, and along the lines of negotiations that had been started by the second President, Terris Moore, a contract was entered into between the ONR and the University whereby the University became the operator of ARL and provided the director and staff.

U.S. interest in ice islands, those ghostly wanderers in the Arctic Ocean, broken originally from the ice shelf bordering a part of Canada's Ellesmere Island, began in 1952 with the discovery and occupancy by the Air Force of T-3, Fletcher's Ice Island. Soon continuing programs on ice islands, and occasionally on sea ice, were initiated by the Navy through NARL. Those programs still go on. A colourful chapter in the story of ice-island occupancy and in the record of NARL was the discovery, the use from May 1961 to May 1965, and the dramatic abandonment between Iceland and Greenland of ice island ARLIS II.

Ice-island programs were spurred in 1954 by the east to west transit of the Northwest Passage by the icebreaker, Her Majesty's Canadian Ship *Labrador*, under Captain, now Commodore O. C. S. Robertson (Ret.). Further interest was occasioned by the U. S. Navy's demonstration that the Arctic Ocean can be used by nuclear-powered submarines.

Now, of course, we have the intense interest in oil exploration and development in northern Alaska, triggered by the announcement of the significant discoveries by Atlantic Richfield and associated companies. Once again the value of the research over the years through NARL is being demonstrated.

The establishment and early operation of NARL were made possible by the oil exploration of Naval Petroleum Reserve No. 4 from 1944 to 1953. The encouragement and cooperation of the Office of Naval Petroleum and Oil Shale Reserves and of the Bureau of Yards and Docks were unflagging. The help provided was based on the deep-seated conviction of the value of the research effort. Many times support was given at substantial sacrifice and inconvenience of the oil-exploration effort. That confidence in the value of the research program was well placed.

Now about the men who were on the bridge as NARL proceeded through the years — the distinguished men who were its directors. They constitute a unique group. Lest it be thought that the life of the director was at any time a bed of roses, let me assure you that such was not the case. Each of those men was competent, strong, dedicated, and each left his distinctive imprint on NARL and, I expect, vice versa.

And behind the director, back in ONR in Washington, were others equally devoted to the Laboratory and equally key to its well being and progress. On that level were carried on the broad planning and program definition. There were waged some of the critical struggles and there were hammered out some of the arrangements that influenced profoundly the shape and nature of NARL.

Although space allows but a word or two, I want to name some of the people in those two groups and to indicate the nature of the roles they played. First, I give you the key figures who operated from ONR headquarters —

1. A leader in the development of the idea of a laboratory, and its actual initiator, was M. C. Shelesnyak, physiologist, with special interest in stress physiology, thermal regulation, human ecology, and polar research. Shelesnyak was a Lieutenant Commander in the new Office of Naval Research as the ideas began to develop. By early 1947 he was Dr. Shelesnyak, Head, Environmental Biology Branch, Medical Sciences Division, ONR. Shelesnyak reviewed the requirements for Arctic research. Then he related those requirements to the general and specific needs of the Navy. Finally, he came up with a plan consistent with the principles of operation of the ONR, that contained the stated requirements of the Navy bureaus and offices, that was coordinated with Government and non-Government research interests, and that took advantage of the services and facilities of the Navy's oil-exploration camp at Barrow.

2. In the fall of 1949 Dr. John Field, also a physiologist, took over the responsibility of the ARL in the ONR. Shelesnyak had left ONR to open and head the Baltimore Office of the Arctic Institute. Dr. Field at that time was the Head of the Ecology Branch of ONR, and ARL responsibilities were added to his other duties. Field recently had come to ONR from the Physiology Department of Stanford University. To his lot fell the making of a number of changes in the contractual arrangements between the university contractor, by that time the Johns Hopkins University, and ONR as well as several organizational changes within ONR itself. He remained at the helm until June 1951. At that time the responsibility

for ARL was established within the Geography Branch of ONR, but it was visualized as an independent project not a subordinate section of the Branch.

3. Dr. L. O. Quam was Head of the Geography Branch and thus appeared on the scene a man who was identified with the Arctic and with NARL for a long time. Through his efforts on the Washington front the Laboratory weathered many crises, several of which could have resulted in the termination of NARL had it not been for the persistence and continuing effective efforts of Louis Quam. Now he has changed his polarity and currently is Chief Scientist of the U. S. Antarctic Research Program within the National Science Foundation. However, no one doubts his continuing interest in the Arctic and more specifically in NARL.

4. In the spring of 1955 negotiations were begun that by fall were to bring to ONR in Washington Dr. M. E. Britton, botanist, formerly of Northwestern University. He had carried out field work at NARL previously and so already was familiar with the facility. Dr. Quam soon assumed broader responsibilities in ONR and Britton took over the direct jurisdiction of NARL from the Washington end. Much of the record of the stability and the growth of NARL from 1955 has been the direct result of the total dedication, self-sacrifice, and plain hard work of Dr. Britton. He continues to battle for NARL at every turn. It augurs well for the Laboratory that he still is on board.

Now we turn to the other group, the former directors and the present director of NARL.

1. First at the helm, as I have already mentioned, was a biologist, Laurence Irving. He is a man of broad vision and a true lover of the Arctic. To him fell the critical tasks of defining the first contractual relationships between ONR and the sponsoring educational institution, in that case Swarthmore College. The operating arrangements between the sponsoring institution and the director in the field at Barrow; the multitude of relationships with ARCON, the Pet 4 prime contractor; the Officer in Charge of Construction of Budocks at Fairbanks and the Resident Officer in Charge of Construction for the oil-exploration program at Barrow, also were his immediate concern. In addition he largely designed the operating pattern between the director and ONR; he established the first research program; developed liaison with the local people at Barrow and with the local airlines — I could go on and on.

2. In July 1949 George MacGinitie took the wheel. MacGinitie is a marine biologist of great stature and broad experience. At NARL he had a common touch that endeared him alike to visiting generals and ambassadors, to tractor drivers and Eskimo workmen, and to laboratory scientists and itinerant research supervisors. He is quite a man — kindly, gentle, sympathetic, humorous — but tough as hickory when necessary.

3. Just over a year later, in August of 1950, MacGinitie was followed by Ira L. Wiggins, distinguished botanist and Head of the Natural History Museum of Stanford University. Many difficult problems arose during his regime and he faced them squarely and unequivocally. In the research field he stood out in his chosen discipline but also he had an uncanny appreciation of the problems of

others in different disciplines and, as director, cheerfully shouldered their burdens too. As I will mention later, Wiggins really had two tours as director, but I am introducing him only once. Wiggins remained as director until the end of January 1954, the longest tour of duty for a director up to that point.

4. Then came my old and good friend, Ted C. Mathews, an engineer, and the only non-scientist to hold the position of director. Ted came on board at the end of January 1954. At that time the contract for the operation of NARL was made with the University of Alaska along lines planned by President Terris Moore but finalized by his successor, Ernest Patty. Pet 4 had been terminated only a few months before and new arrangements had to be made and new relationships established. Ted had been a key figure in ARCON throughout most of Pet 4 and had served with distinction. He knew the background intimately, and he brought the ship onto a new course in a new environment and one that soon began to log an impressive record of accomplishment.

5. About mid-April 1955, Matthews was relieved by Dr. G. Dallas Hanna, a geologist of admirable breadth and understanding from the California Academy of Sciences. His inquiring mind probed deeply many obscure corners that were wonderfully illuminated thereby. In addition, his genius with instruments and his manual dexterity were widely acclaimed and most useful. He and his wife were well loved in Barrow and his tour was one of notable progress.

6. After Hanna, Wiggins returned again, as I have already mentioned, for about 6 months from the end of March 1956 to the end of September of the same year. And so to the bridge at the end of September 1956 came Max C. Brewer, and he is still firmly in command at NARL. I first knew Max Brewer as a young, promising geophysicist in the Geological Survey who became involved at NARL in a permafrost project. Soon his interests far beyond his own project became abundantly apparent. Then he became the director and now he is in fact generally recognized as Mr. Arctic or Mr. Barrow, and he has done an outstanding job.

The record of NARL is replete with accounts of situations, incidents, and crises that reflect somewhat the atmosphere of the local environment, the excitement, the occasional dangers, the feeling of accomplishment, the humour, and some of the rewards of being a part of the activity. I want to pass on to you four of these accounts in which the wording has been modified only slightly from the original reports in order to try to give you the feel of life and work at NARL.

The first is the final chapter in the abandonment of ARLIS I, a floating station on sea ice that by late March 1961 had drifted 615 miles since its establishment in September 1960 to a position some 300 miles northwest of NARL. As the winter wore on it became apparent that the station was in an area of weak ice and would have to be abandoned. The seven men aboard were in an increasingly difficult situation. The report goes on: "cracking became more serious near the end of the year (1960). One fracture crossed the runway and passed close to the camp. Another went under the fuel dump, and still another opened nearly six feet between one hut and the kitchen-mess hall. There was no ice within two miles of the camp that could serve as a runway for heavy aircraft but the Cessna's could still operate in the camp area." The station was abandoned on 25 March and the report describes the operation: "some idea of the task is best described by the team's actions in the last hour and a half on station. The R4D aircraft homed on the beacon, buzzed the camp, and landed on a refrozen lead one and a half miles away. The generator used for the beacon was immediately shut down and the group left for the airplane pulling the generator on a sled behind the weasel. On arrival at the plane, the generator, weighing 2300 pounds was dismantled into three sections and loaded aboard the aircraft. The weasel transmission, a scarce part at Barrow, was removed and, with 1700 pounds of other freight, was loaded. The men climbed aboard and the plane took off. The entire operation took only ninety minutes and the R4D kept one engine running the entire time."

The second account was of an incident relatively early in the course of NARL's activities. It was midwinter and a visiting Fairbanks musician was giving a concert in the Barrow Presbyterian Church attended by the local Eskimos and visitors, many from NARL, to a total of around 400 people. Highlights were reported as "a NARL researcher amusing a restive Eskimo baby during a rendition; two smacking reports from a cap pistol fired by a fun-loving chap in the back row; the large baby chorus that picked up each refrain; and the crowd stepping carefully over sleeping children as the Church was cleared after the concert."

October 1963 was the month of "the storm." The storm was without parallel in the recorded or legendary history of the area, although a series of heavy storms occurred in 1964. The report goes on: "the peak of the storm occurred between 1400 and 1600. Water rushed through the camp reaching a depth of 24 inches in front of the main Laboratory complex and as deep as three and a half feet in other areas. Building 161, the beachmaster's hut, the theater, and F-5 were moved off their foundations and the 40 x 100 foot gym collapsed. Building 161 came to rest out on the tundra behind Building 355. Salt water poured into Fresh Lake in a stream 2 feet deep and as wide as the distance between the camp and the airport. All women and children were evacuated from the camp to the DEW Line site. The force of the current through camp was so strong that only tractors could be driven through the streets. A wolf, two wolverines, and three foxes drowned in this period. One weasel and one tractor were sunk trying to save the animals."

And finally a comment or two about visitors to NARL; the constant coming and going of distinguished visitors was, and is, a common feature of life there. A high point of some sort in this respect occurred in mid-July 1965. Several Air Force and Navy officers arrived on the evening of the 14th. The next day, while the earlier visitors were still there, the Canadian Coast Guard ship *Camsell* arrived for several days stay. At 1300 on the 15th a group of high ranking military officers and university presidents arrived overhead and landed after 45 minutes circling because of a low ceiling. A Navy aircraft with Senator Ernest Gruening and the Commandant of the 13th Naval District appeared at 1515, circled because of the low ceiling and landed at 1630. "That one was rough," the director reported. "On their final approach the hydraulic line on the plane ruptured, the plane landed with only half the normal flaps, they pulled the emergency brake, blew four tires, and one set of wheels plus the nose wheel of the C-54 ran off the runway and buried themselves in the loose gravel. No one was hurt and we unloaded the Senator and the Admiral down the ladder in a completely unflustered condition."

And so it has gone for nearly 25 years. In the words of a former president — "let's look at the record."

About 1500 persons played a significant role as individual researchers or as members of research teams up through 1966. Many of them were repeaters — that is they worked out of NARL during more than one season. Over all there were 784 projects through 1966 — of which 393 were new and 391 repeaters. Of those 393 new projects, 191 were in the physical sciences and 140 in the biological sciences. The remainder were mostly in the social sciences with a few in such fields as development, testing, and engineering.

Seventy-four North American universities have been represented by principal investigators or research teams. They include 4 Canadian universities. The 70 U. S. universities are in 32 states and the District of Columbia. Incidentally, the University of Alaska has had more projects than any other university: 69. Also represented have been 4 Japanese universities, 2 Danish, 2 English, 1 Swedish, 1 German, 1 Irish, and 1 Brazilian.

Also participating have been many semi-educational institutions like the Riksmuseet of Stockholm, the National Museum of Canada, the National Science Museum of Japan, the New York Botanical Garden, the Smithsonian Institution, the California Academy of Sciences, the Woods Hole Oceanographic Institution, and the Scripps Institution of Oceanography.

Many Government agencies also have used NARL as a base for projects. Among these are the Office of Naval Research, the Naval Electronics Laboratory, the Naval Civil Engineering Laboratory, the Naval Ordnance Laboratory, the Naval Underwater Sound Laboratory, the Bureau of Yards and Docks, the Naval Oceanographic Office, the Naval Mine Defense Laboratory, the Army Corps of Engineers, the Army Materiel Command, the Walter Reed Army Medical Center, the Air Force Cambridge Research Laboratories, the Air Force Aeromedical Laboratory, the Geological Survey, the Fish and Wildlife Service, the Department of Agriculture, the Environmental Science Services Administration, the Coast and Geodetic Survey, the Weather Bureau, the National Bureau of Standards, the Public Health Service, the Arctic Health Research Laboratory, the National Institutes of Health, the Atomic Energy Commission, and the National Aeronautics and Space Administration.

ONR should, and I am sure does, take deep pride in what was one of its first major efforts, for the office itself was very new in 1947. NARL's accomplishments, the patterns it has set, its many successes that far outweigh its few inevitable failures, must be viewed with great satisfaction. Its presence today on the platform of rapid development of northern Alaska where the results of its earlier work are so urgently needed and so gratefully applied is indeed opportune

The Atmospheric Circulation and Arctic Meteorology

F. KENNETH HARE[1]

In a sense this title contains a fallacy. Meteorology is the most global of all sciences in outlook, and it can be argued that there is no longer any such thing as *arctic* meteorology, at least in the free atmosphere. Fifteen years ago this was not so. We knew so little of the atmospheric circulation near the pole that it was legitimate to use the title, as I did when in 1954 I founded the Arctic Meteorology Research Group at McGill University (around a program of research transferred from the University of California at Los Angeles). The purpose of our research, and of a sister group at the University of Washington under R. J. Reed, was to bring an understanding of the role of the Arctic into the mainstream of meteorological knowledge. This has now been achieved, and the title is hence anachronistic.

Although it is no longer valid to talk of a specifically arctic meteorology, it is still true that the Arctic plays a special role in the planetary climate, in at least three domains.

At the ice/atmosphere interface over the Arctic Ocean and Greenland the very special energy régime is crucial to the present global climate. This régime has been the special interest of a group of meteorologists including F. I. Badgley, M. I. Budyko, Y. P. Doronin, J. O. Fletcher, M. K. Gavrilova, M. S. Marshunova, L. R. Rakipova, S. Orvig and E. Vowinckel. Norbert Untersteiner of the University of Washington, who has made major contributions to this study also reported at the Symposium, (see pp. 195-99), and as I have elsewhere (Hare 1968) summarized the status of the work, I shall make no attempt to add to what Dr. Untersteiner has said.

In the troposphere the work of Reed's group, of the Arctic Forecast Team at Edmonton (Canadian Meteorological Service), and of C. V. Wilson and others at McGill has shown that a distinctive arctic synoptic régime can be defined. This régime extends into the lower stratosphere up to 20 km. (15 km. in summer). In the stratosphere and lower mesosphere it has been demonstrated (for review see Hare and Boville 1965) that the annual cycle is also highly distinctive, though not necessarily independent of the layers below.

I shall briefly review the advances made in this fifteen-year period in our knowledge of the tropospheric and stratospheric circulations. Dynamic meteorology is not a field where a facility like the U.S. Naval Arctic Research Laboratory can offer much help, since research depends on global data-gathering by analysis centres elsewhere. Nevertheless the surface observations from the drifting ice stations, and from radiosonde ascents made at some of these stations, are in the highest degree relevant. Point Barrow has thus at least a strong kinship with the work I am describing.

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TROPOSPHERIC CIRCULATION

Synoptic analysis over the north polar region became a practical possibility in the early 1950's, when the newly established surface and radiosonde stations in arctic Canada, Alaska and Greenland were joined by the various temporary drifting stations over the Arctic Ocean. Together with the longer established stations in arctic Scandinavia (including Svalbard and Jan Mayen) and the Soviet Union, these stations have created a thin but fairly adequate basis for analysis of the circulation up to 23 km. (30-mb.), and less adequately to 30 km. (10-mb.). More recently meteorological rocket soundings from a few stations have enabled us to get a rough picture to 60 km., in the lower mesosphere.

Throughout the year the basic circulation of the troposphere above 1.5 km. (or 850-mb.) consists of the familiar circumpolar westerly vortex. In summer (Fig. 1) the westerlies extend into arctic latitudes, but at other seasons (Fig. 2) the Arctic is covered by a cold barotropic core lacking organized circumpolar motion, and often containing one or two closed cold lows. Maximum velocities in this westerly ring and in the cold lows are at about 7 to 10 km. Above this level, zonal circulation decreases. In winter, however, as the polar-night westerlies of

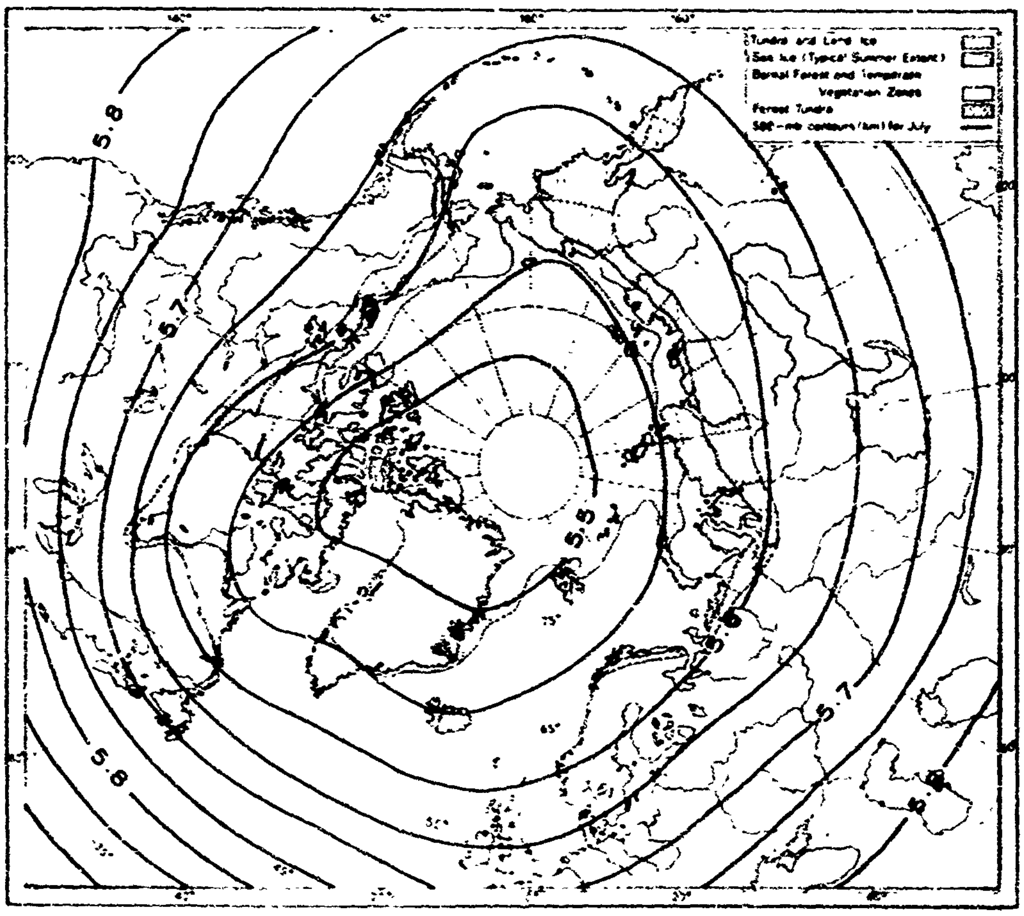

FIG. 1. Mean topography of 500-mb surface (km) and related physical distributions for July. Contours are streamlines of resultant winds.

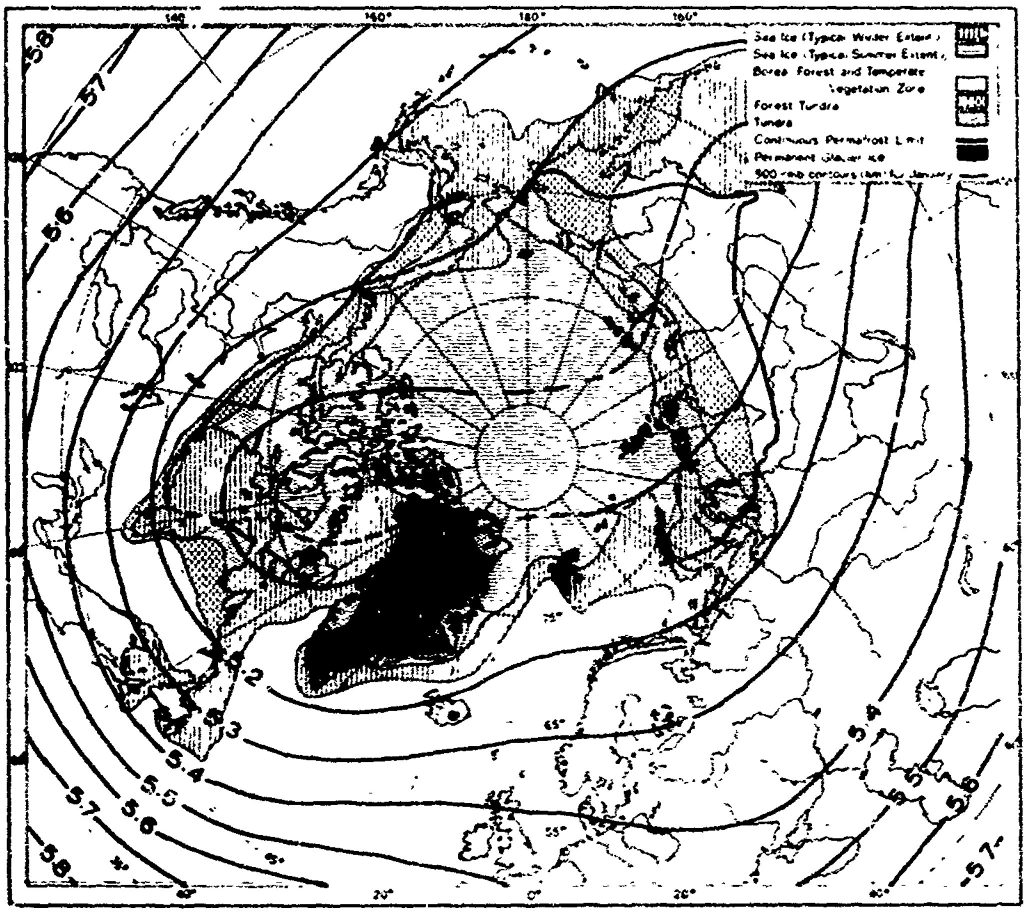

FIG. 2 Mean topography of 500-mb surface (km) and related physical distributions for January.

the stratosphere are entered, westerly components tend to increase again as low as 15 km. In summer westerly flow is rarely detectable above 15 km.

The northern part of the westerly current is strongly baroclinic and one can usually detect an arctic jet-stream and an arctic front within it. This front lies, on the average, across Alaska at all seasons, whereas over Eurasia and North America it undergoes strong seasonal shifts. In summer it lies close to the arctic tree-line, but in winter it moves south to the deep continental interiors. In North America it is then close to the southern limit of the Boreal Forest formation (Bryson 1966; Hare 1968). The complexity of the land/sea distribution in arctic Eurasia makes a surface location difficult between 60° W. and 40° E. In mid- and upper-troposphere, however, the arctic jet maximum can often be observed not far from the 5.4 km. contour for the 500-mb. surface even in those longitudes.

It has been usual to associate this frontal jet-stream system with surface temperature contrasts and frontogenesis. At times, especially in summer, the net radiation field is indeed such as to create airmass contrasts (Fig. 3) near the line of the front (Reed and Kunkel 1960). But the baroclinity is strongest in the upper troposphere, and it is very likely that the arctic front is primarily the product of horizontal eddy-mixing processes tending to produce homogeneity over the inner Arctic, as originally proposed by Flohn (1952). If this is so, then the position of the front and jet reflects large-scale hemispheric dynamics rather than local surface differences. The arctic jet is strongly affected by standing circumpolar wave number 2 (Van Mieghem 1961), which has maximum amplitude (at 500-mb.) in about 60 N., and which has a strong seasonal phase shift reflecting *hemispheric* heating inequalities.

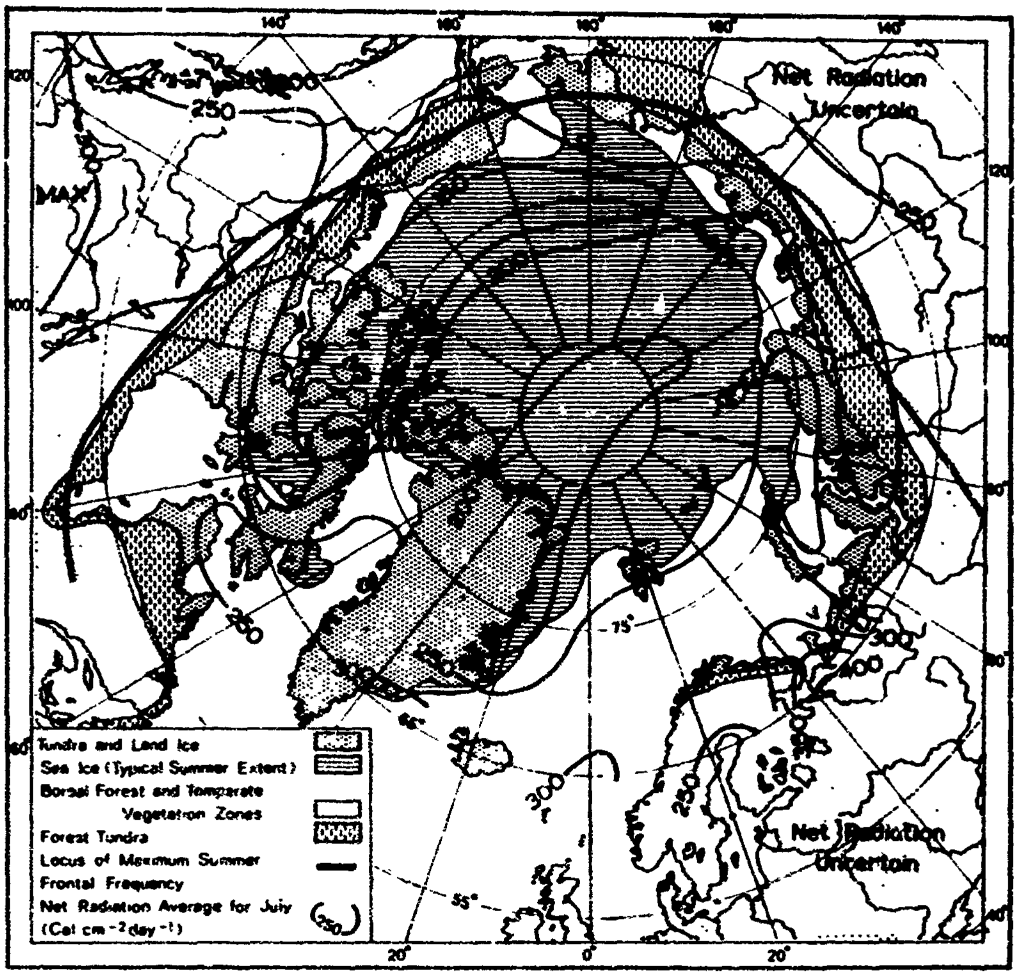

FIG. 3. Axis of Reed-Kunkel (1960) maximum of summer frontal activity in relation to estimated net radiation (ly day^{-1}) for July.

The arctic jet seems to be baroclinically unstable, and is affected throughout the year by eastward-moving cyclone waves. These produce most of the warm-season rains in subarctic and arctic land areas, including Siberia and Alaska. In winter they are mainly features of subarctic Canada and western Siberia, but the "western disturbances" of north and central China belong in the same family. Along the Atlantic flank of the Arctic, deep occluded cyclones often penetrate via the Norwegian and Barents Seas, and may persist as cold lows within the arctic core for long periods. We have thus learned to think of the Arctic as a cyclonically dominated area, though the low humidities of the air-streams involved reduce the associated cloudiness and precipitation. Anticyclones do, of course, occur, and along certain paths — notably southeastwards across Canada and east Asia — regularly move out of the Arctic into the main westerly belt. Only in spring do they dominate the surface weather map over the high Arctic, however.

I shall not discuss the more familiar aspects of the tropospheric climate — the properties of arctic air, the arctic inversion, precipitation distribution and other features; the past fifteen years have not radically altered our knowledge of these things.

THE STRATOSPHERE AND MESOPHERE

Above 15 km. the Arctic is the core of a seasonally reversing circumpolar vortex seemingly distinct from the tropospheric westerlies. In summer, from May until mid-August, light easterlies blow along almost circular paths around a warm Arctic whose high temperatures trace back to absorption of the continuous solar irradiation by ozone. In high latitudes these easterlies are almost undisturbed, though in mid-latitudes westward-drifting troughs and ridges affect the flow (Muench 1968). The easterlies extend to above the warm stratopause at about 50 km. where arctic temperatures are above 0°C. The base of the easterlies is near 15 km. over the arctic ocean coasts, and at about 23 km. in mid-latitudes (Hare 1960).

This régime reverses gradually between mid-August and late September; progressive cooling of the entire stratospheric column creates westerly flow around a centre near the pole, which links downwards with the tropospheric westerlies. During October and November cooling intensifies in the darkening polar stratosphere, and the westerlies of winter become more baroclinic and much stronger; over Alaska, the Bering Sea and adjacent regions of Siberia, however, the cooling ceases, and the stratosphere becomes and usually remains warm for the rest of winter. This creates a powerful stratospheric ridge over or west of Alaska (Boville 1960) which is one of the startling discoveries of the past fifteen years.

The Alaskan ridge deforms the stratospheric polar-night westerlies up to at least 55 km., as rocket evidence shows (Teweles 1965; Frith 1968). The westerlies constitute a cold-cored vortex centred in the mean between Svalbard and Cape Chelyuskin (Fig. 4). Temperatures are near −80°C. at the centre in the 25-30 km. layer, but the stratopause at about 50 km. is believed still to be warm even in mid-winter (Murgatroyd *et al.* 1965). Intensely baroclinic westerlies surround the centre, maximum temperature gradients being over northern Alaska.

Like its westerly counterpart in the troposphere, this higher-level system of the arctic winter is highly disturbed, but neither the overall dynamics nor the character of the disturbances is fully understood. The layer between 15 and 45 km. (and probably higher) is subject to spectacular temperature changes, especially sudden warmings that may raise temperatures 30° C. or more in a day. These changes necessarily involve major wind changes at all levels. Originally an extraterrestrial radiative source was suspected (Scherhag 1952), but it now seems certain that subsidence (or uplift) of the order of less than 5 km. per day can account for the observed changes of temperature and kinetic energy.

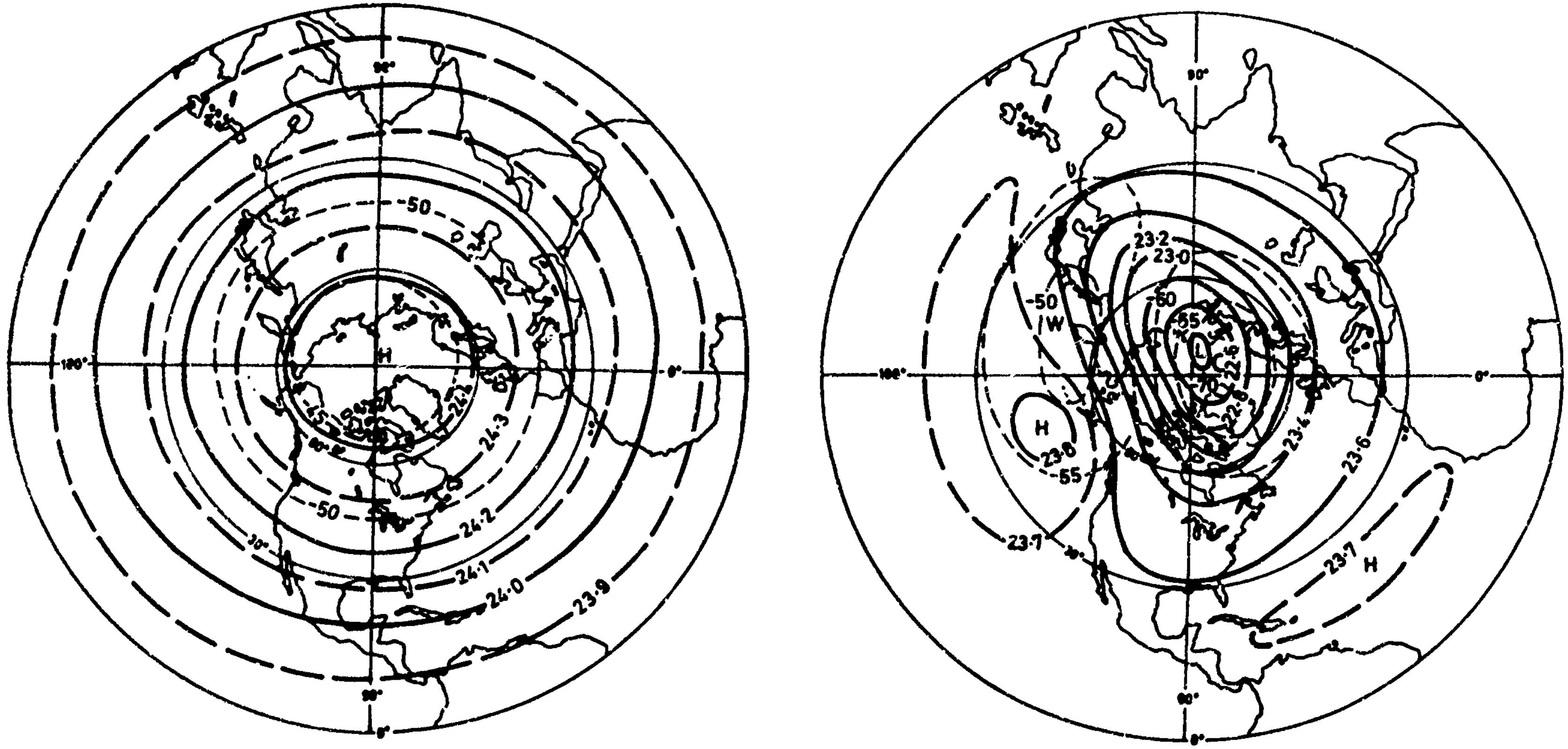

FIG. 4. Mean topography of 30-mb surface (km) for summer and winter, 1958-61. Contours are streamlines of resultant winds, from east in summer, from west in winter. Charts also show temperature in degrees Celsius.

These events show themselves dynamically as large changes in the eccentricity or disturbances of wave numbers 2 and 3 that contribute most of the wave energy at these levels (Fig. 5). Occasionally shorter troughs (of wave number 4 or 5) appear to amplify over arctic Canada, east of the intense Alaskan baroclinity, and these have been interpreted as baroclinically unstable systems generating kinetic energy (Boville *et al.* 1961). In general, however, it appears to be very likely that the energetics at these levels depends on events at lower levels, and is not usually self-generated.

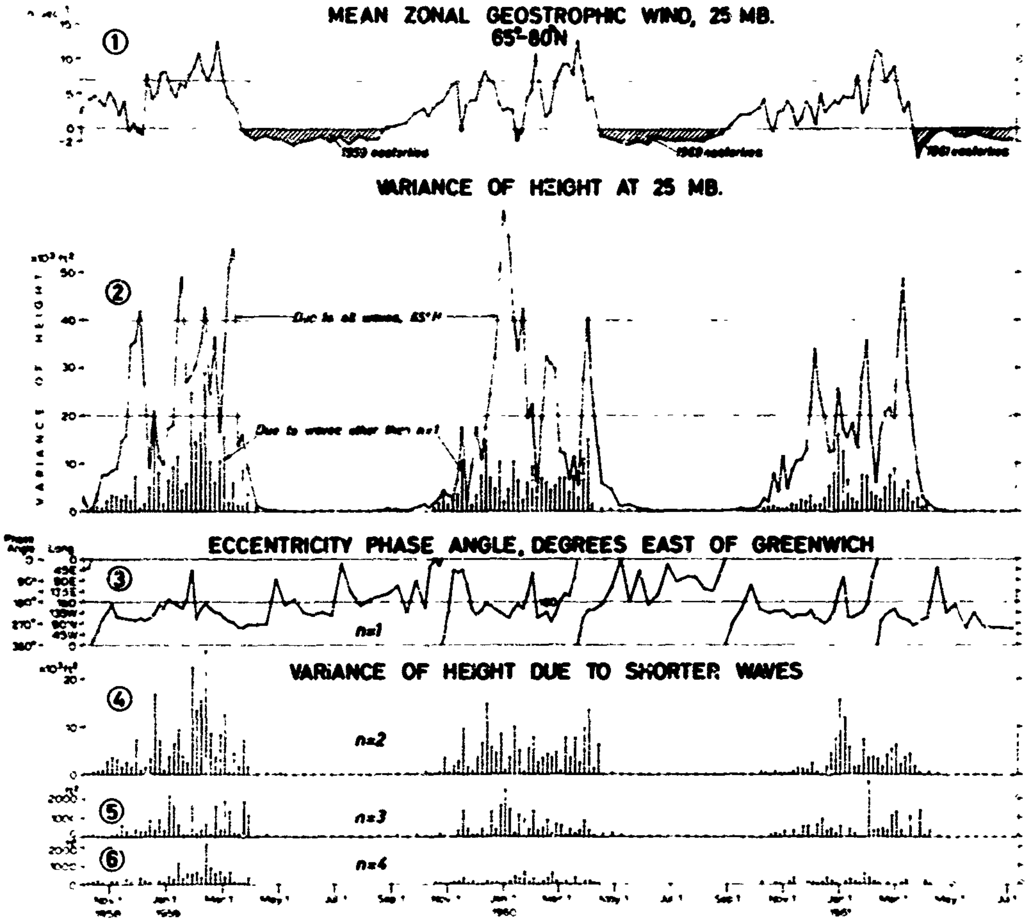

FIG. 5. Wave climatology for 25-mb surface along 65° N, 1958-61. The variance of height, resolved by wave number, shows how the disturbance energy was distributed through three years of stratospheric history. The summer easterlies were undisturbed.

The westerly vortex collapses spectacularly at the end of winter, with the final warming episode (Wilson and Godson 1963). This consists of one or two centres of subsidence that rapidly break up the system. For a few weeks the stratosphere and mesosphere have rather disorganized flow, but by early or mid-May easterlies are re-established through most of the column, and are completely dominant for the rest of summer. The spectacular dynamical warming that precedes this régime comes at widely variable dates, and cannot be ascribed to renewed solar warming of the ozone layer.

The composition of the lower stratosphere reflects these processes. In the layer of 12 to 25 km., but especially in that of 16 to 18 km., the thermal structure is remarkable for the existence in northern mid-latitudes of the stratospheric warm belt. This separates the deep, cold, tropical tropopause belt from the cold north polar cap, except for about three summer months. The air of this stratospheric warm belt is believed to be excessively dry, with frost points of about −80°C. (approximately the temperature of the tropical tropopause). In the late winter and spring it also appears to be invaded from time to time by high ozone-content air, presumably introduced by subsidence in association with the stratospheric disturbances just described. It has been shown that some of the short-period fluctuations in total ozone in the air column reflect the motion of stratospheric disturbances (Allington *et al.* 1960; Boville and Hare 1961), and the spring maximum of ozone similarly relates to the final warming episode (Godson 1960; Hering and Borden 1964).

DISCUSSION

I hope that I have been able to show that we have now a good picture of the annual pattern of events in the high latitude circulation up to the stratopause and basal mesosphere. Most of the theoretical questions raised by the discoveries of the past fifteen years are, however, still open. Among these I would isolate the following as worthy of much further work:

1) The relationship between the circulation within the tropospheric arctic core and the rest of the general circulation is still imperfectly understood. Most general circulation numerical experiments are based on realistic assumptions about the westerly belt, and tend to generate a single baroclinic westerly current. Experience in high-latitude analysis, however, suggests that multiple baroclinity and jet-structure may be typical of the circumpolar vortex, and that the arctic front and jet must arise from hemispheric patterns of heating and cooling, rather than from local frontogenesis. An adequate theory of the general circulation must explain the existence of this structure.

2) The dynamics and energetics of the polar night westerly vortex require further analysis, as does its interaction with the tropospheric westerlies beneath. That such interaction must occur, and must be critical to the behaviour of the upper level vortex, is intuitively probable, and theoretically predicted by Charney and Drazin (1961) and Charney and Stern (1962). Proof of such interactions depends on sophisticated forms of spectral analysis. Recent studies by Muench (1965), Perry (1966), Byron-Scott (1967), and Paulin (1968) have begun to establish the form of the connections, and to relate it to theory; but much remains to be done, particularly as regards the origins of the quasi-permanent Alaskan ridge.

3) Finally, the entire question of eddy and radiative transfer processes on all scales requires attention at stratospheric levels. The problem of the existence of the stratosphere, and of the overlying mesosphere, is still one depending on the radiative balance and its interaction with the circulation. And the problems caused by its curious composition — dryness, ozone richness, aerosol distribution — are

equally to be approached from both the dynamical standpoint of this paper and the standpoint of exchange processes for mass and energy, with which I have not dealt.

In all these problems high latitude conditions are of major interest. Hence it is very suitable that I should end by wishing the new facilities of NARL all success. I hope that the scientists who use it will be conscious of the remarkable things going on over their heads.

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Sea Ice and Heat Budget

NORBERT UNTERSTEINER[1]

In April 1957 a group of scientists arrived at Ladd Air Force Base to man the first long-term U.S. drifting station on sea ice. Considering how much, twelve years later, we still have not found out, our innocence at that time might have been disheartening. But, luckily, innocence never is.

I am sure that our small research group at the University of Washington had a thoroughly thought-out program at the time, and the questions to ask might have been the following:

1) What are the properties of sea ice?
2) Why is the Arctic Ocean ice-covered?
3) Under what circumstances could the present ice cover change?

Needless to say, these three questions are closely connected, especially the second and the third.

In dealing with the first question, properties of sea ice, an important distinction is to be made between the small-scale (sample size) properties and the properties of a large, natural sheet of sea ice, or in other words, between sea ice as a material and sea ice as a geophysical phenomenon.

A great deal of work has been done on the properties of sea ice as a material. Owing to the work of Weeks and Assur (1967), Peyton (1963), Schwerdtfeger (1963), and many others we have now accumulated a substantial amount of knowledge on the crystallographic structure of sea ice and on its mechanical and thermal properties. We also have a fair amount of knowledge of the radiative properties although here considerably more work remains to be done, for instance, on the attenuation of light in sea ice and on radiative properties in the microwave region.

All properties of sea ice are profoundly affected by its salt content. From the work of Assur and Weeks we have now a fairly clear idea of how the partition of ice and salt occurs during the freezing process and how the brine is distributed in the initially formed ice. We also have known for a long time that the ice, which originally has a salinity of several parts per thousand, becomes practically fresh after a few years. This process of desalination, however, is still largely unknown and offers a field of fascinating and useful research.

In general, it seems fair to say that sea ice as a material is reasonably well known and that those points that are to be cleared up are easily identified and will no doubt be taken care of in the near future.

Much less favourable is the situation in regard to the properties of large, composite sheets of natural sea ice. In the present context of the general heat and ice budget of the Arctic Ocean there are three parameters that are most important:

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strength, roughness, and albedo. None of them do we know accurately enough to be confident in making the calculations that will be discussed later. And all three of them have a common requisite: knowledge of the actual morphology of the ice. What the shape and size of a sample are for the experimenter in the laboratory, distribution of ice thickness, leads, and ridges are for the geophysicist in the field. It is our lack of knowledge of the morphology of the ice that makes it so difficult to evaluate its properties.

Strength: This is the most problematic parameter. It is needed for calculations and predictions of the movement of the ice. More specifically, we need to know how a large sheet of natural sea ice is deformed by stress under the action of wind and water currents that contain areas of convergence, divergence, and shear. It is hopeless to theorize on this problem, and even the design of a meaningful experiment, relating the distributions of air and water stresses to ice strains, contains fundamental difficulties that will not be overcome without the execution of a rather vast observational project.

Roughness: This is the parameter that describes the efficiency of the frictional coupling between the air and water flows and the ice. We have some idea what the roughness length of smooth, undisturbed ice is. But the drag on those areas may be outweighed by the form drag on ridges and hummocks at both sides of the ice, and we cannot hope to calculate accurately the stress to which the ice is subjected if we don't know its topography.

Albedo: The annual total of incoming short-wave solar radiation is of the order of 70 kcal. cm.$^{-2}$. About 25 or 30 per cent of that is absorbed at the ice surface. The absorption coefficient is very sensitive to the areal extent of water puddles in the summer and of open leads (which are nearly black). A decrease of the albedo of only 2 per cent would cause an increase in absorption equivalent to 20 cm. of ice melted. Of course, the albedo has been measured by numerous investigators but most of these measurements were made too close to the ground and do not accurately represent areal averages. Nothing is known about the range of year-to-year variations of average albedos.

There are, of course, other large-scale parameters that are important as, for instance, the transmission of light through the ice into the ocean, but those mentioned are the most crucial in the present context.

The second main question is concerned with the explanation of the existence of the present ice cover. Since the presence or absence of ice is determined by the temperature at the surface, and since the temperature at the surface is determined by the fluxes of energy into and out of the surface, the determination of these energy fluxes is the only approach to an explanation of what happens at the surface. It is trivial to say this now, but it was not until the 1930's that this approach, or the so-called heat balance method, became commonly adopted.

To explain sea ice we first have to establish a number of observational facts. From the numerous observations made at the drifting stations we know that the total accumulation of snow is about 40 cm. with a density of 0.35 g. cm.$^{-3}$, that the mean monthly surface temperatures range from about 0° in July to about −32°C. in February, that the snow usually begins to melt around the tenth of June, that it is melted away by the end of June, and that subsequently about

40 cm. of ice are melted away, balanced by an equal amount of new ice formed at the bottom during the winter months. Thus an "equilibrium ice thickness" is established that is generally believed to be around 3 m. These observations have been fairly easy to make, and they established what it is that has to be explained.

The next set of observations concerns the energy fluxes. These observations are much more laborious and, since the International Geophysical Year they have been a major part of the activities of our group at the University of Washington. They consist of measurements of radiative fluxes, both visible and infrared, albedos, wind and water flow profiles in the boundary layers, temperature profiles in the air and in the ice, and evaporation or condensation. These observations are fraught with a long list of difficulties, ranging from plain instrumental inaccuracies to problems of sampling and representativeness. The most extensive and thorough efforts in combining all this information into a coherent picture of the overall heat balance have been made by Fletcher (1965) at the Rand Corporation and by Vowinckel and Orvig (1966) at McGill University. The picture that evolves is, of course, not free of unexplained inconsistencies but, in general, they are minor and we now have at least a working knowledge of the thermodynamic behaviour of the ice and of the energy fluxes that cause it. To tie these two together and to develop a formal, mathematical way to describe thickness and temperature changes of the ice as a result of climatic and oceanic forcing functions has been our main effort during the past five years.

The details of our numerical model cannot be described here (Maykut and Untersteiner 1969). In brief, the model predicts surface temperature, surface ablation, bottom ablation or accretion, internal temperature, and snow or ice thickness, caused by a given set of input functions consisting of incoming short and long-wave radiation, turbulent fluxes in the air, and snowfall. With Fletcher's heat balance values as input functions, the model produces a sheet of ice that behaves, in its thermodynamic aspects, almost exactly the way it is observed in nature. In other words, it seems that our second main question, "Why is the Arctic Ocean ice-covered?", has been answered at least partially. Even though we have not said how the ice got there, we have explained in quantitative terms what keeps it there.

The third main question, "Under what circumstances could the present ice-cover change?", leads us not only to the heart of the problem but also into a vast area of unresolved and exceedingly complex questions.

The real ice cover is only very crudely approximated by the simple, semi-infinite sheet of ice that we have described in our model. In reality, the forces of wind and water currents act on the ice and cause the contorted drift patterns that we know from our stations, the large stream of ice that is continuously pushed out into the Greenland Sea, and the open leads and pressure ridges that modify the heat exchange to an unknown degree.

A numerical model for the drift of sea ice under the influence of wind and water currents has been developed by Campbell (1965) at the University of Washington, but this model cannot be used for actual drift predictions as long as the internal stress parameters, mentioned earlier, are unknown.

Given the interaction between the thermodynamic and the dynamic behaviour of the ice, and given the fact that any major variation in the extent of the ice cover would also influence the atmosphere, which in turn interacts thermodynamically with the ice, it becomes clear that we have here a three-phase-system of air, ice, and ocean, that interacts on a global scale with a built-in variety of multiple feedbacks. Our ability to parameterize such a problem is deficient and our computers are still too slow, but there is no doubt that it will be solved since the present limitations are in data and data-processing rather than in concepts and ideas.

The "heart of the problem" mentioned earlier in this section is the purported "instability" of the arctic sea-ice cover. On the basis of some rather qualitative arguments it has been theorized that this ice cover, once removed by some climatic anomaly (natural or artificial), would not return. The drastically lowered albedo of an open Arctic Ocean would result in an amount of heat storage during the summer that would prevent the formation of more than a thin skim of winter ice. The historical record speaks against such an instability. The work of Hunkins and Kutschale (1967) and Ku and Broecker (1967) at Columbia University indicates that the Arctic Ocean has been ice-covered for at least 150,000 years. Recent work done at the University of Wisconsin (Steuerwald *et al.*, 1968) suggests that this might have been so throughout the entire Quaternary, if it is true that the present rate of sedimentation is indicative of an ice cover and low productivity in the ocean. However, the interpretation of these findings still seems to leave some room for doubt, and even the remote possibility that the arctic ice cover might be unstable in the above sense makes this problem one of extreme importance from a scientific, economic, and even political point of view.

When our project started in IGY 1957, logistical support was provided by the Alaskan Air Command. Perhaps there are records of the cost of this operation. If there are, it is best not to look at them because they would be misleading. Station Alpha was a "first" and a conspicuous success, whatever price was paid, and I doubt that the relative economy and efficiency of the later drifting stations would have been possible without the experience gained by the first one.

Since 1959 we have been logistically supported by the Naval Arctic Research Laboratory, and this seems an appropriate time to thank Max Brewer and his staff for their efforts and hospitality. I should add that NARL not only supported the field activities mentioned earlier but also an extensive program in air chemistry and radiation climatology at Barrow.

Speaking for the thirty-odd people that have worked for our project and who have, in part, gone on to either greater or lesser things, I should like to direct an expression of particular gratitude to two addresses: one is Phil Church, who initiated our whole project and saw it through its first turbulent years, and the other is Max Britton and the Office of Naval Research, who have been staunchly supporting us with money and encouragement, and who have given us the new Naval Arctic Research Laboratory.

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Polar Ionospheric Research

VICTOR P. HESSLER[1]

INTRODUCTION

The short wave electromagnetic radiation from the sun has sufficient energy to cause photo-ionization of the gases in the upper atmosphere. The resulting ionized region ranging in height from about 50 km. to 1000 to 2000 km. is called the ionosphere. The possibility of such a conducting layer was postulated in 1878 by Balfour Stewart to account for the daily variation of the geomagnetic field and was given additional credence in 1902 by Kennelly and Heaviside in explanation of the seemingly anomalous propagation of wireless signals across the Atlantic Ocean. The existence of the ionosphere could no longer be questioned after the classic pulsed radio experiment of Breit and Tuve in 1926.

The first indication of trapped particles in the earth's magnetic field, far above any trace of the atmosphere, was given by the inter-hemispheric propagation of lightning-induced electromagnetic wave propagation along magnetic field lines: whistlers. By the mid 1950's calculations based on the dispersion of whistlers had shown that electron densities of the order of 400 cm.$^{-3}$ existed at an altitude of 12,000 km. in the region now called the magnetosphere. The magnetosphere may be defined as the region in which the geomagnetic field energy density is greater than the kinetic energy density of all charged particles and thus their motions are under magnetic field control. The magnetosphere extends from about 500 km. to several earth radii on the sunward side and to many earth radii on the nightside (Fig. 1).

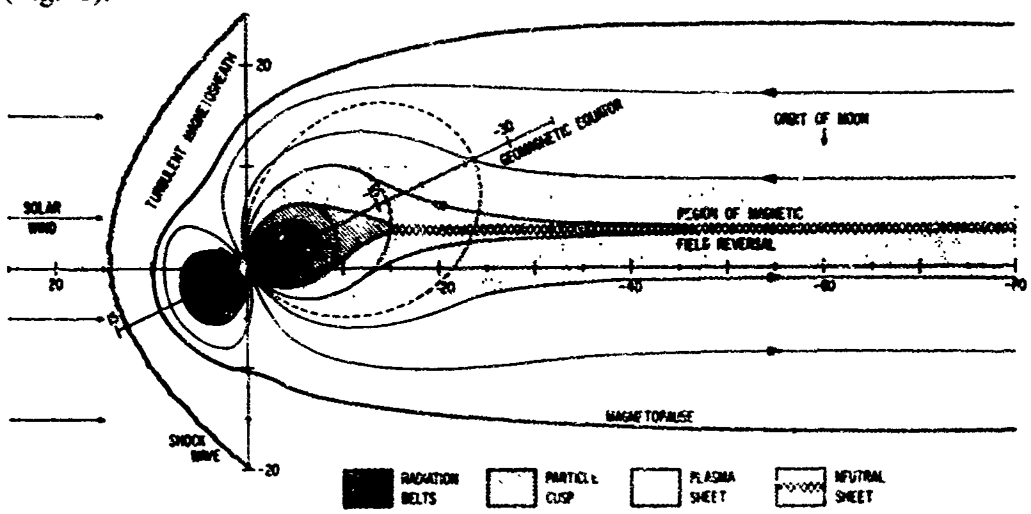

FIG. 1. Present-day view in noon-midnight magnetic meridian plane of the geomagnetic field and tail as distorted by the supersonic solar wind. A detached bow shock forms upstream from the magnetosphere and leads to the development of the turbulent boundary layer, the magnetosheath (From King and Newman 1967).

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From a practical point of view knowledge of the ionosphere and its variations is essential to all aspects of radio communications other than ground wave and line of sight transmissions. The Ballistic Missile Early Warning System radar signals must traverse most or all of the ionosphere twice and thus are subject to varying amounts of absorption and refraction in the highly active polar ionosphere. In addition spurious reflections from auroral-type activity may block extensive areas of the field of view. Electric currents in the ionosphere produce magnetic and telluric variations at the ground. Under disturbed conditions the variations may make it impossible to conduct geophysical prospecting involving magnetic and telluric techniques.

DESCRIPTION OF THE IONOSPHERE

Perhaps the most important ionospheric parameters are the height profiles of charge density, atmospheric pressure, and electron, ion, and neutral particle temperatures (Fig. 2a, b). These parameters determine the particle collision frequencies and the critical radio frequencies at the various levels of the ionosphere and

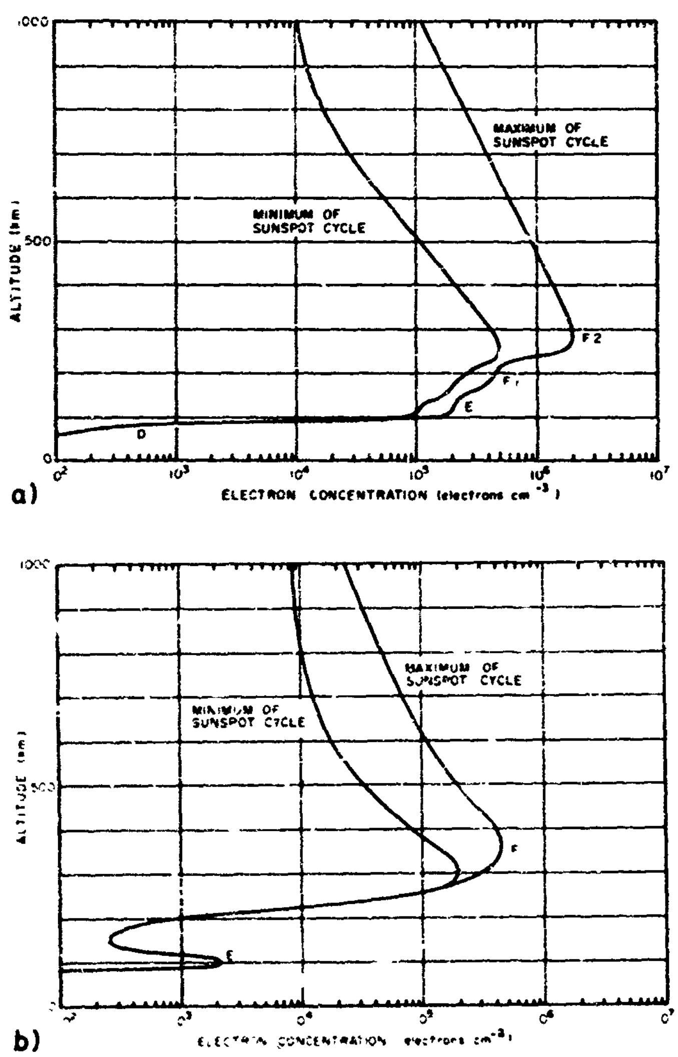

FIG. 2. Normal electron distributions at the extremes of the sunspot cycle: a. Daytime; b. Nighttime (From Johnson 1965).

thus the refraction and absorption of radio waves. Knowledge of the molecular and atomic constituents at the various levels is essential to an understanding of the absorption cross section of the solar electromagnetic radiation and the resulting ionization.

The electrical conductivity of the ionosphere together with the mechanical and electrical driving functions determine the magnitude and direction of the current density vector in the various regions and levels of the ionosphere. The guiding effect of the earth's magnetic field upon the moving charges results in anisotropic conduction and thus a tensor conductivity. The two important components of this tensor from the standpoint of resulting ionospheric currents are the Hall and Pederson conductivities (Figs. 3 and 4).

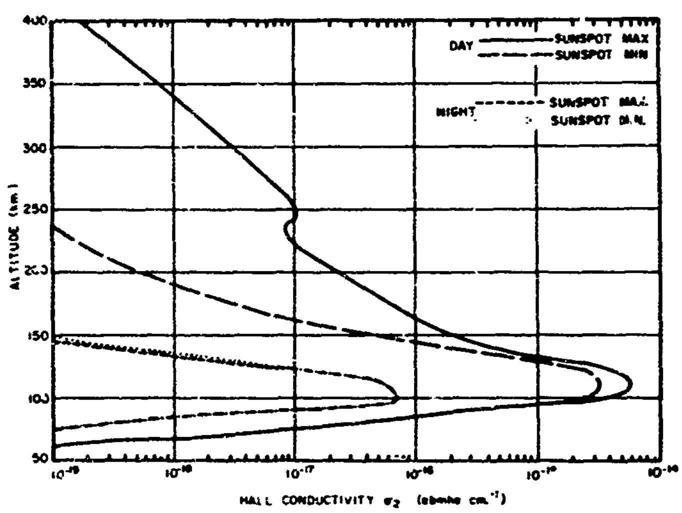

FIG. 3. Hall conductivity σ_2 versus altitude (From Johnson 1965).

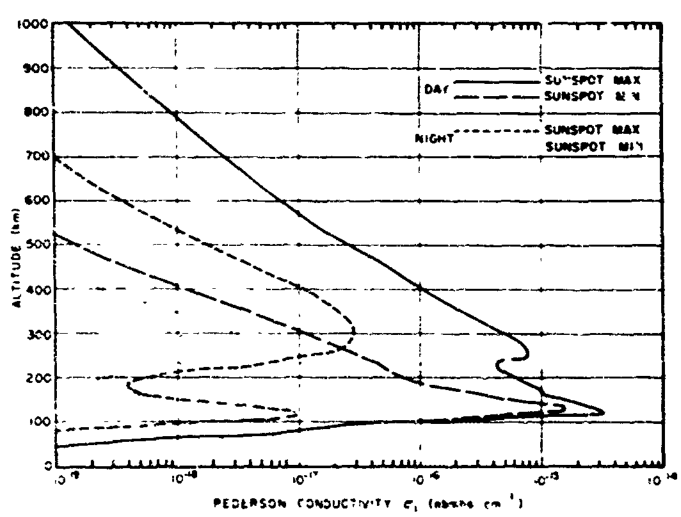

FIG. 4. Pederson conductivity σ_1 (reduced conductivity) versus altitude (From Johnson 1965).

Ionospheric Regions

The ionosphere divides naturally into three horizontal layers or regions based on distinct physical characteristics and ionization processes. The regions are termed the D-region, the E-region and the F-region from the bottom to the top of the ionosphere, with further subdivisions of the E- and F-regions.

THE QUIET D-REGION

During undisturbed solar conditions the daytime D-region extends from a height of about 60 km. to 85 or 90 km. (Fig. 1). The electron density of the quiet daytime D-region is of the order of 10^3 cm.$^{-3}$ at 80 km. and decreases to 10 cm.$^{-3}$ at 60 km. The lower D-region ionization essentially disappears on a quiet night (Fig. 2b). Electron density values are of the order of 10^3 cm.$^{-3}$ at 90 km. and 10 cm.$^{-3}$ at 80 km., down from the daytime level by 2 orders of magnitude. Owing to the high collision frequency in the D-region its conductivity is too low (Figs. 3 and 4) to permit appreciable electric currents to flow. Thus the D-region contributes very little to magnetic variations observed at the surface of the earth.

The practical importance of the D-region lies in its high rate of absorption of radio waves. Under normal daytime conditions there is essentially no ionospheric reflection of 0.05 to 1 MHz waves; thus communications in this band are limited to line of sight or to ground waves: the well known day-night effect in the broadcast band.

THE QUIET E-REGION

The boundaries of the E-region, as stated in the various references, range from 85 to 90 km. at the bottom and from 140 to 160 km. at the top. The E-region electron density at the noontime, quiet sun condition is of the order of 10^5 cm.$^{-3}$ (Fig. 2a). The density is about 50 per cent greater during sunspot maximum. The major variation from day to night is noted by comparing Figs. 2a and b, which show nighttime electron densities of approximately 2 to 3 orders of magnitude less than the daytime values. The maximum conductivity of the ionosphere in directions corresponding to existing driving functions, such as the dynamo and tidal actions, is located in the E-region. As noted above, the conductivity is low in

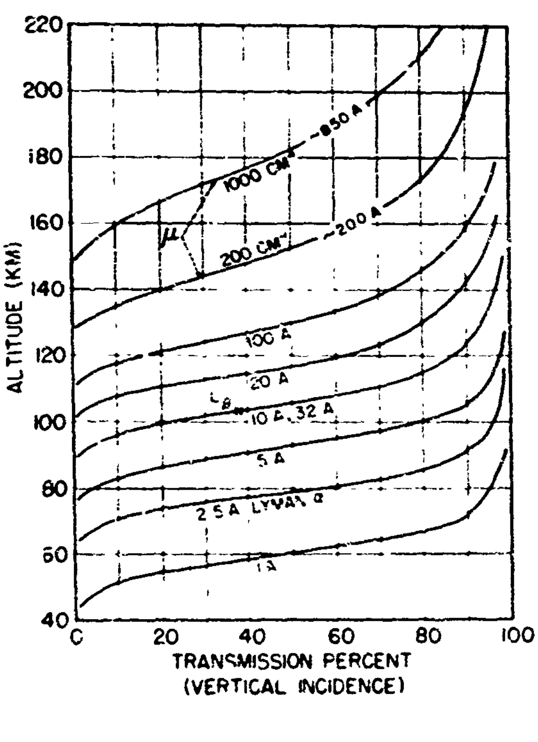

FIG. 5. Atmospheric transmission in X-ray nd ultraviolet ionizing wavelengths when the sun is overhead. The limits of the shaded band are drawn for absorption coefficients of 200 and 1000 cm^{-1}. Almost the entire wavelength range of 200 to 850 A is included within these limits. The cross marked Lyman-β indicates unit optical depth in that wavelength (From Ratcliffe 1960).

the D-region because of the high collision frequency. In the F-region the collision frequency is very low in comparison with the spiralling frequency perpendicular to the magnetic field lines, and thus any driving function across the magnetic field produces little net forward motion. In the E-region the collision frequency is of the same order of magnitude as the spiralling frequency, thus the spirals are broken up and the net forward motion increases. The auroral electrojet flows in this relatively high conductivity path.

The primary ionizing radiations of the E-region are solar X-rays (10 to 100 Å), the hydrogen Lyman β line (1025.7 Å), the doubly ionized carbon, C^{++}, line (977 Å), and the hydrogen Lyman continuum (910 to 800 Å) (Fig. 5). The characteristics of the daytime E-region are very well known. These characteristics are such as to give a good radio reflection in the frequency range of the vertical incidence sounder. The delay time gives accurate height information and electron density is determined from the critical frequency. The E-region is monitored routinely by more than 100 ionosondes distributed throughout the world. The practical importance of the E-region lies in its relative low absorption and effective reflection of radio waves in the frequency band from about 1 to 3 MHz thus permitting long-distance radio communications in this frequency band. Daytime radio transmissions for distances up to 2000 km. generally take place via the E-layer.

THE QUIET F-REGION

The F-region consists of two layers, F1 and F2. The lower layer, F1, ranges in height from 140 to 200 km. (Fig. 2a) and is characterized by both the well-behaved E-layer below and the variable F2 layer above. Like the E-layer, it disappears at night and is related to solar zenith angle (Fig. 2b). Typical noontime electron densities range downward from 2.5×10^5 cm.$^{-3}$ at sunspot maximum. The principal ionizing agent of the F1 layer is the solar ultraviolet in the wavelength band from 200 Å to 900 Å. The ions are principally NO^+ and O_2^+ at the lower boundary and O^+ at the upper boundary. The deep valley above the residual nighttime E-region (Fig. 2b) cannot be recognized on the ionosonde records. Knowledge of this region is dependent on rocket-borne detectors. With the disappearance of the F1 layer at night the F2 layer becomes synonymous with the F-region.

The F2-region ranges from 200 km. to 1000 to 2000 km., the lower limit being determined by electron density and the upper by ion composition considerations. Long distance radio communication between ground-based stations is possible only because of refraction in the F-layer. The various radio warning services publish predictions of MUF (maximum useable frequency) values which are based on measurements of electron densities and anticipated solar activity.

The Disturbed Sun

The solar electromagnetic radiation ranges from radio wavelengths through the visible, ultraviolet, to X-rays of less than 1 Å. The continuum radiation is relative constant even in the ultraviolet, but the shorter wavelengths increase materially at sunspot maximum and the very short wavelengths show striking increases with solar flare activity. For example, studies of solar electromagnetic energy flux show ratios of maximum to minimum solar intensity of 7:1 for wavelengths <200 Å, 60:1 for wavelengths <20 Å, and 600:1 for wavelengths <8 Å. The hard X-rays are very flare sensitive. One measurement of 2 to 8 Å X-ray flux during a class 2+ flare shows an increase 770,000 times the sunspot minimum, quiet sun value. In contrast such measurements normally show only several per-cent increase in Lyman α (1216 Å). The solar wind also increases appreciably with sunspot activity. Under quiet solar conditions typical values are 5 protons cm.$^{-3}$ at a velocity of 500 km. sec.$^{-1}$ ranging to 10 protons cm.$^{-3}$ at 1500 km. sec.$^{-1}$ for disturbed conditions.

The Disturbed Ionosphere

The advent of a solar disturbance, particularly a class 2 or 3 flare, results in major changes in the characteristics of the several ionospheric regions.

THE DISTURBED D-REGION

There are three significant types of D-region disturbances associated with increased solar activity, particularly with solar flares. They are termed "sudden ionospheric disturbances" (SID), "auroral absorption events", and "polar cap absoption events" (PCA). An SID is characterized by a sudden increase in absorption of MHz-frequency radio waves in the sunlit hemisphere with maximum attenuation at the subsolar point and decreasing monotonically to the twilight region. Its onset is normally precipitate and simultaneous with the visual appearance of a major flare. The attenuation gradually decreases to the pre-flare level over a period of 60 to 90 minutes. The increased low-level ionization responsible for the attenuation is produced by the 1.0 to 10 Å X-rays associated with the flare (Fig. 5).

Auroral absorption, an auroral zone effect, is considered to result from the precipitation of energetic electrons into the upper D-region. It is predominantly a nighttime effect associated with active auroras and magnetic disturbances. The concept of the PCA event dates from the IGY period. "The very heavy radio absorption which began less than an hour after the great west-limb solar flare of 23 February 1956 and whose onset occurred during the most intense outburst of solar cosmic rays yet recorded, was the first generally recognized case of high-latitude absorption that could not be considered as merely a special case of auroral absorption." (Bailey 1964). It is now known that these PCA events are caused by low energy solar cosmic rays — protons with energies from 300 to approximately 5 Mev. (The most pronounced PCA event in several years occurred at the close of the Naval Arctic Research Laboratory Symposium completely disrupting radio communications from NARL to the north.)

THE DISTURBED E-REGION

Variations in the E-region due to solar disturbances generally appear in the form of thin enhanced layers of ionization called Sporadic E. The source of the Sporadic E ionization is not well understood. However, in the case of the aurorally-associated Sporadic E the agency must be energetic particle bombardment, but how the particles can produce such thin layers is not at all clear. The role of Sporadic E in radio communications is quite complicated. The layers serve as reflectors with a wide range of possible ray paths, involving multiple reflections at the earth and from the E and F regions. The reflection from a Sporadic E layer may occur either at the top or bottom of the layer.

THE DISTURBED F-REGION

The first observation of an F-region disturbance was made at Slough, England, in 1935. The disturbances are characterized by a marked decrease in the F2 layer critical frequency and electron density at mid and high latitudes and by a corresponding increase at low latitudes.

IONOSPHERIC RESEARCH TECHNIQUES

Until the advent of high altitude rockets and of satellites, all ionospheric investigations were of necessity indirect. Most of the techniques are based on analysis of radio wave reflection or refraction and attenuation in the frequency range from about 10 to 50 MHz. The whistler techniques extend the useful spectrum down to about 300 Hz and below this the magnetic and telluric field techniques utilize the band in the range from about 50 to 0.001 Hz plus diurnal variation effects. At the other end of the spectrum, the spectral lines, intensity, and morphology of the visual aurora provide significant information. With the advent of rockets and satellites direct measurements of the various ionospheric parameters became possible as extensions of the radio techniques. Only some representative techniques will be mentioned.

Optical techniques

THE ALL-SKY CAMERA

The all-sky camera provides a minute by minute record of the auroral morphology out to a radius of about 800 km. from the camera. Since auroral luminosity is closely related to electric charge precipitation into the lower ionosphere (because ionospheric currents flow along auroral arcs, and because brilliant and active auroral displays occur at the site of major ionospheric disturbances) a net of all-sky cameras may provide significant information about ionospheric activity over a vast area. The camera also has the advantage of any visual technique in showing the exact location and contour of the disturbance. In a recent experiment all-sky cameras carried on jet aircraft flying along magneto conjugate paths in the northern and southern hemisphere showed a remarkable similarity in the quiet time auroral forms.

AURORAL SPECTROSCOPY

Spectrographic techniques together with photometry and triangulation provide a wealth of information concerning ionospheric processes. With the aid of the diverse techniques available, deductions may be made concerning many aspects of the aurora. For instance, details such as the energy and flux density of the precipitating electrons and protons responsible for auroral excitation, the type of neutral or ionized atom or molecule being excited, and the height at which the excitation occurs may be deduced.

Radio Propagation Techniques

THE IONOSONDE

The "pulse method" of ionospheric exploration, first introduced by Breit and Tuve is by far the most commonly used. The instrument, called an ionosonde, is essentially a pulsed radar (of about 10 kw. peak power) in which the exploring frequency is varied, normally over a range from 1 to 25 MHz. The wave is directed vertically and the echoes are usually recorded on a panoramic display from an oscilloscope with virtual height on the Y-axis and frequency displayed logarithmically on the X-axis. The frequency is normally swept through the 24 MHz in about 15 sec. More than 100 ionosondes are in continuous operation throughout the world.

THE RIOMETER

The riometer, or relative ionospheric opacity meter, measures the absorption of cosmic radio noise in its passage through the ionosphere. The instrument basically consists of a calibrated sensitive radio receiver with an output circuit capable of driving a strip chart recorder. In the frequency range of 25 to 50 MHz the riometer is insensitive to normal D-region absorption but quite sensitive to the increased D-region absorption which accompany SID's, auroral events, and PCA's. At the auroral zone it may be difficult at times to separate auroral and PCA events, particularly at night when electron attachment greatly reduces the PCA effect. However, the incidence of the accompanying auroral event is often delayed from several hours to two days after the onset of the PCA. The riometer provides excellent PCA records during such periods.

VHF FORWARD SCATTER

A forward scatter system consists of a transmitting and receiving station separated by distances of from 1000 to 2000 km. and usually operating in the frequency range from 30 to 40 MHz. The relatively high gain antennas are directed to the lower ionosphere at the midpoint between the sending and receiving stations. Bailey (1964) has made extensive use of the technique for the study of PCA's in the Arctic. The several systems used had midpoints ranging from 60° to 83°N. geomagnetic latitude. The range in latitude corresponded to calculated vertical cutoff energies for protons of from 500 down to 0.09 Mev.

AURORAL RADAR

Auroral radar echoes are observed with oblique incidence sounders operating in the frequency range from 20 to 800 MHz. At lower frequencies the signal may be attenuated too much and at higher frequencies the back-scattering effect is small. As the term implies the scattering electrons in auroral radar are associated with visual auroral phenomena, but the correlation is far from one to one. The scattering irregularities are highly aspect sensitive. Radar reflections at College, Alaska, come from the quadrant bisected by magnetic north and in ranges from 400 to 1000 km. At Barrow where most of the visual aurora is seen to the south, the predominant direction for radar reflection is at a low angle in the general northerly direction. The auroral radar technique seems to have produced only limited results. However, knowledge of its characteristics is, of course, critical to the BMEWS operation.

WHISTLERS

Whistlers are electromagnetic signals in the audio frequency range. They are often preceded by a click followed by a sliding tone commonly ranging from 5000 down to 1000 Hz in about a second. It is now known that the click is propagated directly to the listener from a lightning stroke. Some of the broad-band electromagnetic wave energy from the stroke is transmitted to the ionosphere where it couples to a tube of magnetic flux along which it is guided by the free electrons in the magnetosphere. The energy packet is reflected at the base of the tube in the opposite hemisphere. Since the high frequency components travel faster than the lower frequencies the wave is dispersed and produces the whistler. Whistler analysis has shown that during sunspot maximum the electron density is of the order of 100 $cm.^{-3}$ at 5 earth radii. During a magnetic storm the electron densities in the magnetosphere may drop to one-tenth of the normal quiet day value.

Balloon and Rocket Techniques

Balloons, having a normal ceiling in the order of 30 km. permit the study of only the more penetrating radiations. They have found their most extensive use in the recording of bremsstrahlung X-rays produced when precipitated energetic electrons are brought to rest in the upper atmosphere of the auroral zone. In situ atmospheric and ionospheric measurements in the region between balloon heights and the usual satellite perigees, roughly 30 to 200 km., are made with rockets. In contrast with the several hours duration of balloon experiments, rocket experiment durations are of the order of many seconds to several minutes. Among the many instrumentations and experiments carried aloft by rockets are magnetometers, energetic particle detectors, auroral spectrophotometers, barium cloud ionospheric wind-detecting experiments, and temperature detectors.

The first magnetometer probes of the ionosphere were made in 1948-49 when three triaxial fluxgate units were flown to about 110 km. aboard Aerobee rockets by the Naval Ordnance Laboratory. The next flight, made in 1956, carried a proton precession magnetometer. All succeeding rocket borne magnetometers through, at least, 1964 were either proton precession or rubidium vapor magnetometers. Such flights have determined the height of the equatorial electrojet, and some mid-latitude phenomena; they are now being used to explore the relationship between the auroral electrojet and the visible aurora.

MAGNETIC AND TELLURIC DISTURBANCES

From the standpoint of ionospheric research, magnetic and telluric records taken at the earth's surface are used to a large extent as indices of ionospheric activity. Ionospheric disturbances, particularly in the region of the auroral zone involve marked changes in the ionospheric conductivity and in electric forces. The resulting ionospheric current systems produce magnetic changes on the ground at the auroral zone of more than 2500 γ (5 per cent of the total field). Magnetic observatories and their international associations publish a group of indices which correlates well with various ionospheric parameters. Real time magnetic and telluric records are used to predict radio propagation conditions and, for example, to control release times for balloon and rocket experiments.

Geomagnetic micropulsation studies, while still in the natural history stage of study of the phenomena themselves, begin to provide insight into other magnetospheric and ionospheric phenomena. For example, there is a prominent band of pulsations in the period range from 1 to 5 seconds, with amplitudes from several milligammas to several gammas which are generated in the magnetosphere on closed field lines and propagate horizontally in a waveguide centred on the F_2 peak. Recent studies of the incidence of these pulsations at auroral-zone stations and at the north geomagnetic pole show major seasonal variations in the propagation characteristics of the polar cap ionosphere.

THE AURORAL OVAL

Analysis of the IGY and succeeding all-sky camera data, and other auroral type activity has shown that the precipitation of auroral primary particles occurs in an oval displaced about 3° toward the dark hemisphere. As a first approximation the earth rotates under the oval once a day. The oval may be termed the instantaneous auroral zone, whereas the auroral zone is now considered to be the locus of the midnight sector of the auroral oval. The auroral oval expands and contracts with variations in the intensity of magnetic activity.

POLAR IONOSPHERIC RESEARCH PROBLEMS

An extensive discussion and analysis of the current polar ionospheric research problems is contained in the forthcoming report by the Panel on Upper Atmospheric Physics (1969). The following sections reflect a number of the views and recommendations of the above report.

The Magnetospheric Model

Many aspects of the magnetospheric model are not clearly defined: in particular we lack understanding of the high latitude lines which are swept away from the sun by the solar wind to form the magnetospheric tail.

Auroral Theory

A unifying theory is needed to follow the solar electrons and protons from their incidence and capture at the edge of the magnetosphere, through the magnetosphere to their final precipitation in the polar regions, with the accompanying auroral type phenomena, visual, radio, thermal, magnetic, etc.

The Polar Substorm

Perhaps the most significant progress in polar ionospheric research in the past decade has been the rapid development of the polar substorm concept, the aspects of which are reviewed in detail by Akasofu (1968). Studies of all-sky camera records for several years show that the quiet auroral forms which characteristically lie along the auroral oval are activated intermittently in a disturbance extending all along it. The disturbance originates in the midnight sector and spreads rapidly and violently in all directions. The substorm lasts from one to three hours and is usually repeated every few hours during a magnetic storm.

The auroral substorm is always accompanied by an intense auroral electrojet which is responsible for the polar magnetic substorm. The equivalent current system of the magnetic substorm is assumed to flow in the ionospheric E-region and is inferred from magnetic perturbation vectors, or more commonly from the H or X component at polar magnetic stations. Many of the aspects of the polar substorm are concomitants of the magnetospheric substorm. Studies to date suggest that the intense plasma cloud ejected during a major solar flare generates a shock wave in the interplanetary plasma. If the flare occurs within say a 20° radius around the centre of the solar disk as viewed from the earth the shock wave may produce a sudden compression of the magnetosphere sufficient to trigger explosive processes in the magnetosphere which are responsible for the polar substorm phenomena described above. The magnetospheric-polar substorm complex represents one of the most important of the current polar ionospheric research problems.

RESEARCH PROGRAMS

Routine recording

Our knowledge of the polar ionosphere has progressed to the point where we may perform many special experiments to test new or old hypotheses. Since funding is always a problem and the experiments are expensive there is a temptation to curtail the older programs. However, the value of the experiment often depends materially upon synoptic data from the various observatories. Every effort should be made to keep the polar net of ionosondes, magnetic observatories, forward scatter systems, all-sky cameras, and riometers in operation. For example, for two years, there has been no ionosonde in operation at Thule, the north geomagnetic pole, and now the data are much needed to support the micropulsation analysis.

A polar meridian net

The most urgent need in the continued study of the eccentric auroral oval is a meridian net of magnetic, riometer and all-sky camera stations extending from the geomagnetic pole to say 62°N. geomagnetic. In addition to further delineation of the auroral oval, such a net would provide a frame of reference for polar orbiting satellite data taken in its spatially and temporally-variable coordinate system.

Satellites and rockets

Experiments utilizing satellites and rockets are needed for studies of the D and lower E regions, Sporadic E, distribution in latitude and altitude of ionospheric minor constituents such as atomic oxygen, ozone, water vapor and nitric oxide, and determination of the positive and negative ionic composition.

The importance of ground-based support for satellite research such as magnetometers and all-sky cameras at the base of geostationary satellite L-shells must not be overlooked. Fig. 6 shows that such experiments in the arctic fall within the principal Naval Arctic Research Laboratory support area.

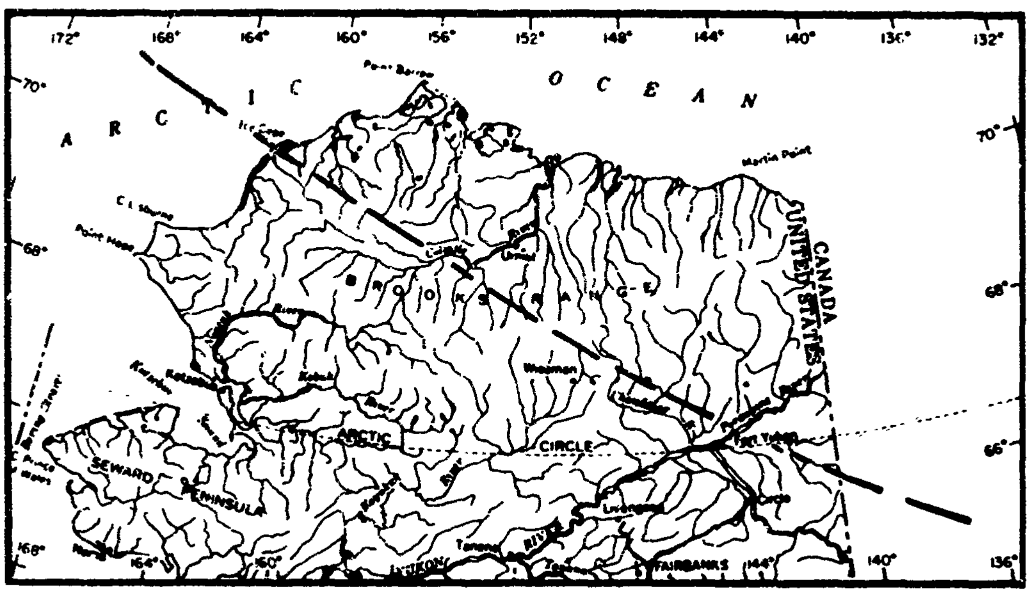

FIG. 6. Locus of the base of L-shells corresponding to a range of geostationary satellite positions over the Pacific Ocean.

LOGISTICS AND FACILITIES

Logistics will presumably always be one of the major problems of polar ionospheric research. In Antarctica the Navy has the capability of placing a research team anywhere on the continent at almost any time but, of course, the expense precludes any but the most urgent programs being situated away from the established bases. In the Arctic NARL has the same type of capability as evidenced by their monumental and courageous support of Arctic drifting station ARLIS II. Their establishment and support of ARLIS III and ARLIS IV exemplifies their capability of supporting individual programs and at a moderate cost.

Future logistics of polar research will surely involve unmanned automatic observatories with telemetry analogous to the current satellite techniques. The Panel on Upper Asmospherics report (1969) states, "The unmanned automatic observatory with real-time communication link has nearly all the observational capabilities of a manned station, as has been demonstrated by various observatory satellites. The experience gained from manned stations has provided enough information to enable the observatories and sensors to be interfaced to the local environment. In addition, an unmanned automatic observatory in the polar regions can provide vastly improved data acquisition capabilities. Data can be transmitted from the field site to the experimenter's laboratory in real time using synchronous satellites."

That NARL will assist in the accomplishment of future polar ionospheric research cannot be doubted. Its record to date, its geographical location, and the interest evidenced by the Department of the Navy all indicate the continuation of its valuable contribution.

ACKNOWLEDGEMENTS

I should like to express my sincere appreciation to the Office of Naval Research and to the Naval Arctic Research Laboratory for the support of my ionospheric research program at Point Barrow and on the arctic drifting stations.

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Marine Sciences

Physical Oceanography in the Arctic Ocean: 1968

L. K. COACHMAN[1]

INTRODUCTION

Three years ago I reviewed our knowledge of the physical regime of the Arctic Ocean (Coachman 1958). Briefly, the Ocean may be thought of as composed of two layers of different density: a light, relatively thin ($\sim$ 200 m.) and well-mixed top layer overlying a large thick mass of water of extremely uniform salinity, and hence density. In cold seawater, the density is largely determined by the salinity. Superimposed on this regime is a three-layer temperature regime.

The surface layer is cold, being at or near freezing. Frequently there is a temperature minimum near the bottom of the surface layer ($\sim$ 150 to 200 m. depth), and within the Canada Basin a slight temperature maximum is found at 75 to 100 m. depth owing to the intrusion of Bering Sea water. The intermediate layer, Atlantic water, is above 0°C., and below this layer ($>$ 1000 m.) occurs the large mass of bottom water which has extremely uniform temperatures below 0°C. but definitely above freezing.

The general picture of the water masses is drawn from 70 years of oceanographic data collection. The Naval Arctic Research Laboratory, in its support of drifting stations and other scientific work on the pack ice, has provided the basic support for the United States contribution to physical oceanographic studies of the central Arctic Ocean.

There are still enormous gaps in our knowledge. The Arctic Ocean is probably no less complex than any of the world oceans, but its ranges of property values are less and hence the complexities are reflected as smaller variations of the values in space and time.

The spatial coverage of even the mean temperature and salinity fields in the water is very spotty; hence our knowledge of the water masses and their interactions is poor, particularly in regard to the quantities involved. This comes about because we have been for the most part restricted to analysing samples from drifting stations, and these stations drift only along certain defined paths. Furthermore, we do not have anything like a synoptic picture of the distributions of these variables. Therefore, our picture of the distributions does not represent the fields in the ocean at a particular time, and in fact may not properly represent the mean fields of temperature and salinity.

The field of motion is much less well known than is the distribution of the water masses. This stems in part from the fact that the motion field has much more "noise" in it than does the temperature field, for example. Also, the measurements we have been able to get suffer from the limitation of being made from a

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moving platform, which causes two problems. One is that the platform motion must be subtracted from the measurements to find water motion, and positioning of the ice with sufficient accuracy and frequency to allow a reasonable separation of ice and water motions has been possible only very recently. The other problem is that inherently time and space variations cannot be separated when the measuring point continually changes position. We have practically no information on spatial variations of Arctic Ocean currents today, but the experiments outlined later are aimed at this problem.

NARL'S CONTRIBUTION TO PHYSICAL OCEANOGRAPHIC STUDIES

An important contribution by NARL is their willingness to support drifting stations. Without this support, our knowledge of the physical character of the ocean would not even be at the present level. If this support were to cease now, there would virtually be no United States physical oceanographic research in the Arctic Ocean.

The most significant particular contributions in the last 20 years can be summarized as follows:

1) We have been able routinely to collect hydrographic data for a number of years from the Canada Basin. Continuation of this data-collection will allow us in the near future, I believe, to analyse for long-term trends in the characteristics of the water masses. Climatic variations can be reflected in small changes in the t and S of ocean water, as has been documented for example for the Greenland Sea (Aagaard 1968) and deep Labrador fjords (Nutt and Coachman 1956).

2) The support of "Ski Jump" in 1951-52 (Worthington 1953) which has been the only U.S. counterpart of the Soviet High-Latitude Air Expeditions. This expedition, even though limited in scope, produced very useful results from the oceanographic viewpoint. Stations were occupied near the central part of the Beaufort Sea gyre which are still the only data we have from this area.

3) The current measurements obtained from ARLIS II while it drifted out of the Arctic Ocean with the East Greenland Current provided significant new ideas about this western boundary current of a subpolar gyre (Aagaard and Coachman 1968a, b). New concepts of the circulation in the Greenland Sea and exchange with the Arctic Ocean were generated by the observations.

4) The recently developed capability of precise and frequent position-fixing of Fletcher's Ice Island, T-3, now permits good direct measurement of the horizontal currents in the deep Arctic Ocean. The initial results from the first series of these direct current measurements are presented below.

CURRENT INVESTIGATIONS — TWO SCALES OF ICE-WATER MOTION

Long-term trends

There have been a number of drifting stations in the last 20 years in the Canada Basin for which reliable positions are available. The drift tracks of those

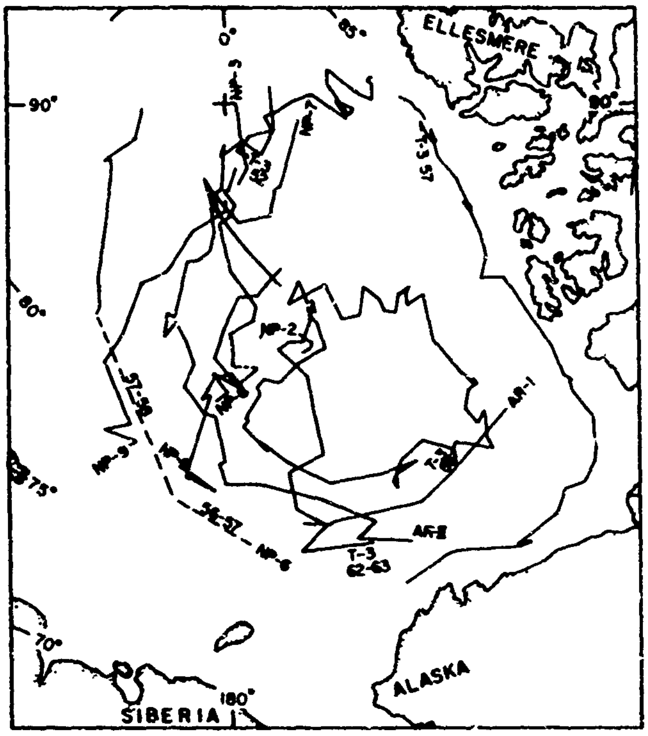

FIG. 1. Ice station drift tracks in the Canadian Basin constructed from segments of net monthly drift. Track of NP-6 is broken as monthly data are not available.

for which positions at the end of each month were available are shown in Fig. 1. Each track is composed of segments of net monthly movement. The tracks define clearly the well-known Beaufort gyre circulation. The centre of the gyre, 80°N. and 140°W., coincides with the centre of the mean atmospheric pressure anticyclone (Felzenbaum, from Campbell 1965).

The day-to-day drift of ice stations has been observed to be quite erratic (see, for example, Fig. 5). To analyse for possible long-term trends the vagaries of the motion were suppressed by using the net monthly displacements. There is a very definite directional preference to the long-term motion for various locations, resulting in the anti-cyclonic gyral pattern of the mean atmospheric pressure field. The inevitable conclusion is that, over the long term, the winds associated with the mean atmospheric pressure field drive the ice in a similar pattern.

As the atmospheric pressure field will vary in intensity over months and years, the speed of ice drift in the gyre can also be expected to vary similarly. However, the speed variations may be different in different parts of the gyre owing to differences in atmospheric pressure gradients, and to time and space variations in the large frictional resistance (Campbell 1965) in the ice cover.

A first attempt to define seasonal and long-term variations in the ice drift was made as follows. All drifts west of 140°W., which are in general directed to the west and north, were separated from those taking place farther east. These segments are identified as being in the Transpolar Drift Stream, while those east of 140°W., where the drifts are predominantly east to west along the Canadian Arctic Archipelago, are in the eastern Beaufort gyre.

The mean monthly drift speeds grouped by months and their standard deviations for the two drift areas are presented in Fig. 2a. The conclusions are:

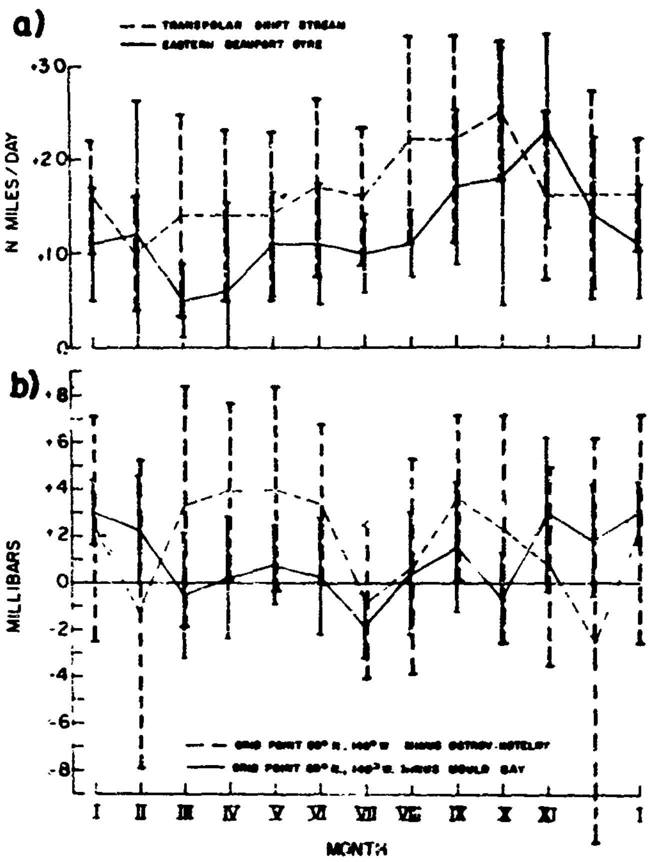

FIG. 2. a) Mean monthly drift speeds and b) mean monthly surface atmospheric pressure gradie , by months, and for the two sides of the Beaufort gyre. Monthly means are connected to show trends, and ± one standard deviation is indicated.

1) Ice drifts faster in the Transpolar Drift Stream than it does along the Canadian islands, by about ½ n. mi./day.;

2) A marked increase in speed occurs in summer or fall. The surge occurs in late summer in the transpolar stream, but not until late fall in the eastern part of the gyre.

As a crude approximation to the surface atmospheric pressure gradients, which must be instrumental in driving the system, mean monthly atmospheric pressure gradients across the east and west sides of the gyre were compiled and treated in a manner identical to the drift data (Fig. 2b.).

For the eastern side, the pressure difference was the mean monthly value for grid point 80°N., 140°W., minus the mean monthly value reported for Mould Bay. For the transpolar side, 80°N., 140°W. minus Ostrov Kotelny was used.

The atmospheric pressure gradient variations agree qualitatively with the drift speed variations in that:

1) The pressure gradient across the eastern side of the gyre is less than across the transpolar drift stream;

2) There is an increase in late summer or fall with the same phase shift between the transpolar and eastern Beaufort sides as observed in the drift speeds.

In addition, there is a marked increase in late winter-spring in the magnitude of the atmospheric surface pressure gradient across the transpolar drift stream which apparently is not reflected in a corresponding increase in drift speed. This

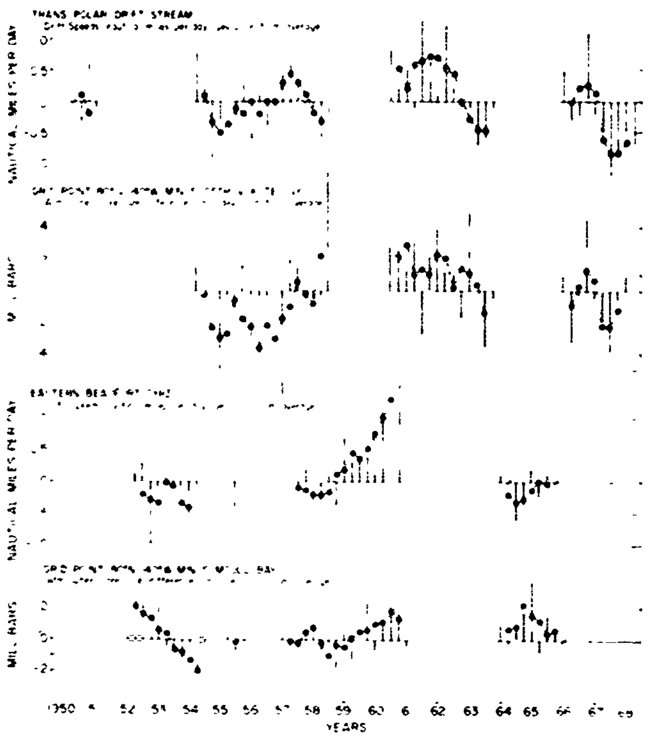

FIG 3. The transpolar drift data and eastern Beaufort data, deviations of drift speeds (above) and atmospheric pressure gradients (below) from the monthly averages, averaged by seasons. Trends are indicated by 3-point running means. Vertical lines are quarterly averages. Seasons indicated are winter (December through February), spring (March through May), summer (June through August), and fall (September through November.

might be attributed to the fact that in winter the ice cover is tighter and heavier and undoubtedly there is a much greater frictional resistance within the pack.

To examine the data for longer term trends, the spatial separation was maintained, the mean monthly speeds averaged by quarters, and then the seasonal variation removed by examining deviations from the quarterly average. The residuals are plotted in Fig 3, which show whether the stations were drifting slower or faster than normal for the location and season. To illuminate trends, three-point running means are also plotted. Below each segment of drift data the comparable atmospheric pressure gradient data, treated identically, are plotted. The conclusions are:

1) There are definitely times when the ice drift has been significantly faster and slower than the average. In the period 1959-62 drift speeds were greater than one-half nautical mile per day faster than normal; recently, beginning in 1967, drifts have been more than one-half mile per day slower than normal;

2) The speed variations are positively correlated with intensity in the appropriate mean atmospheric pressure gradients.

Clearly, there are long-term variations in the ice motion which are related to variations in atmospheric pressure. More detailed research along these lines may well lead to better predictions of ice drift.

Ice and water motion during summer, 1967

During the summer of 1967 the satellite navigation system provided numerous fixes of T-3's position to about ±0.3 nautical mile. Three current meters, at 150, 500, 1300 m. depth, recorded relative water motion at 10-minute intervals over nearly 110 days. This is one of the longest series of deep-ocean current mea-

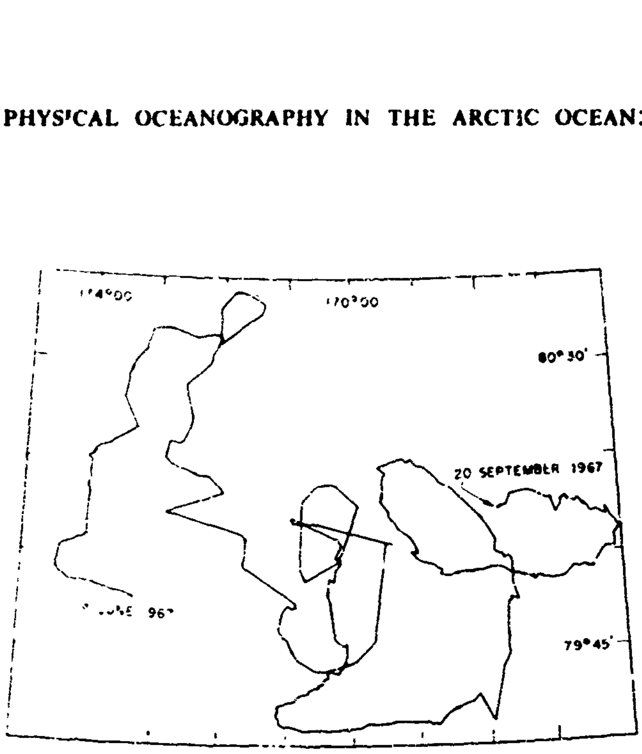

FIG. 4. The track of T-3 between 1 June and 20 September 1967, as determined by satellite navigation. The 1 June position is in lower left, the 20 September position in middle right.

surements that have been obtained anywhere, and considerable information about Arctic Ocean currents in the three water masses and their time variations are in the record.

To convert the relative measurements to actual water motion, the movement of T-3 had to be analysed as thoroughly as possible. Fig. 4 shows the track of T-3 for the 110 day-period. Fixes were examined sequentially in time; those that gave positions of less than 0.3 n. mile (the presumed error) from the previous one were averaged in space and time with each previous fix to generate a new position. By this technique we feel the track has been smoothed as much as possible without reducing the resolution.

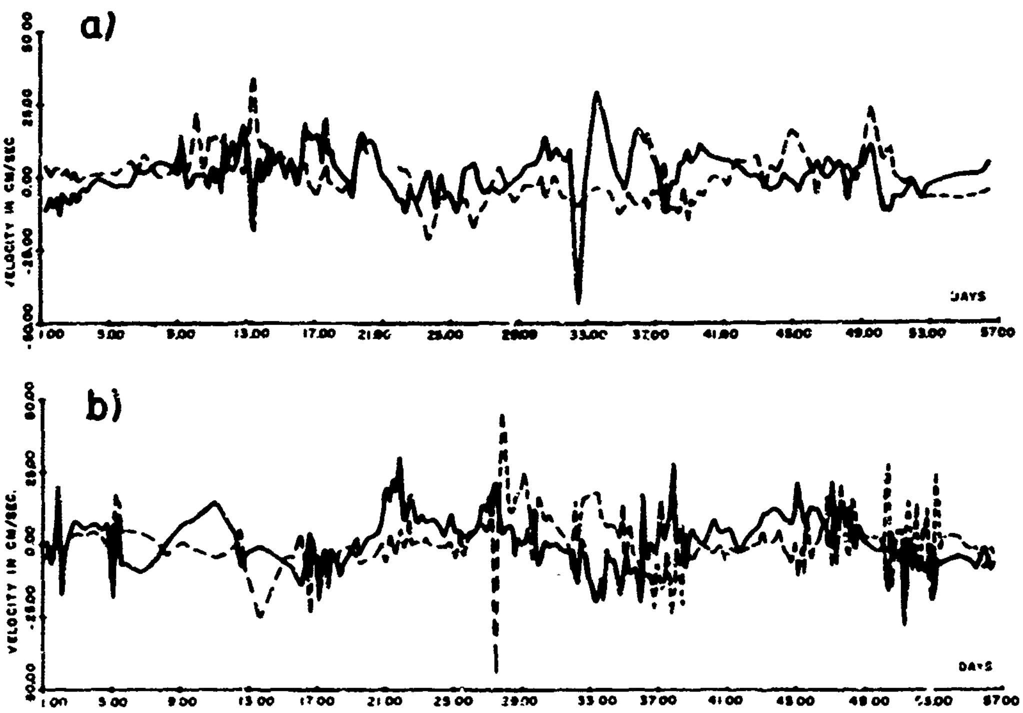

FIG. 5. U (east: solid line) and V (north: dashed line) components of T-3 drift, determined as net motion between fixes, in the period a) 1 June to 26 July 1967, b) 27 July to 20 September 1967.

The track of T-3 took many twists and turns during the summer, and looks like the other drift tracks I have examined. When mean velocities between fixes are calculated and plotted as U (east) and V (north) components (Fig. 5), certain cyclical patterns appear. In both components there is a fairly long period of speed variation so that about four cycles are covered by the record, a periodicity of about 3 weeks. The higher frequency oscillations do not show as well, so the records were filtered.

Cut-off and band-pass filters were used to produce Fig. 6. The upper plot is of all periodicities longer than 10 days. The oscillations with a period of 2 to 3 weeks and speed changes of ½ knot are obvious. A phase shift between U and V shows contra-solem rotation, and this variation, then, corresponds to the cyclonic whorls in the drift track (Fig. 5).

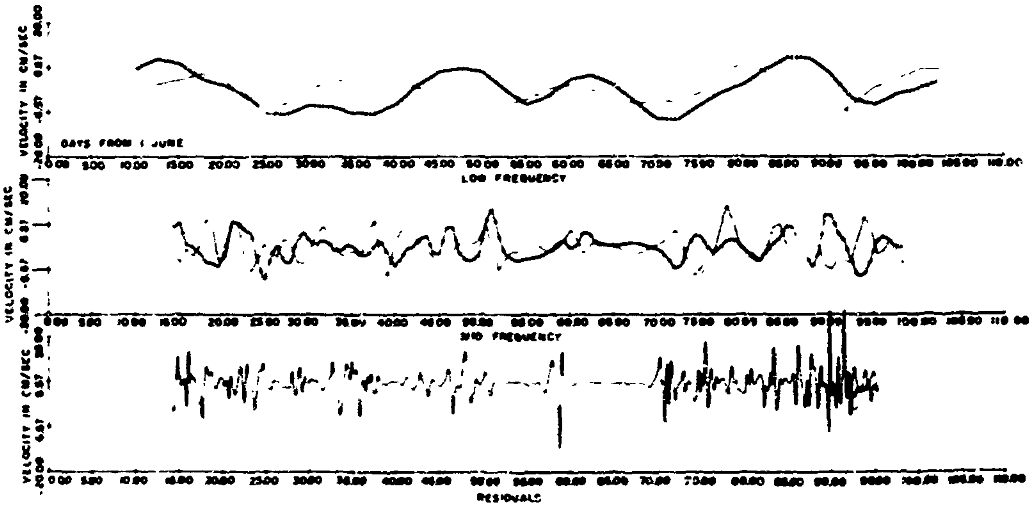

FIG. 6. The data of Fig. 5 filtered such that periodicities greater than 10 days (upper), between 3 and 10 days (middle) and less than 3 days (lower) are exposed. U component is light line. V component is heavy line with dots. Lower plot shows U component only.

In the middle plot of Fig. 6 the components are filtered to leave oscillations with periods of between 3 and 10 days. There is a definite oscillation with a period of about 3 days and amplitude of nearly the same magnitude as that of the long-period oscillation. The phasing between U and V components is quite erratic, and therefore this oscillation is not associated with a regular repeating phenomenon such as a wave.

The causes of the long term and 3 day oscillations most probably are in certain atmospheric phenomena. A cycle repeating every 2 to 3 weeks suggests to me the period for Rossby waves to pass a given location. These, in turn, guide the cyclone tracks, which might have effects lasting 3 days.

The residual after filtering (Fig. 6, lower) shows the seemingly erratic motion remaining, very much like "noise." An unsuccessful attempt was made to isolate diurnal motion, but the scarcity of fixes probably precludes positive identification of frequencies of one cycle per day and higher. In any event, the magnitude of the residual was relatively small and therefore the major portion of the ice motion is variable with periods of 3 days or more.

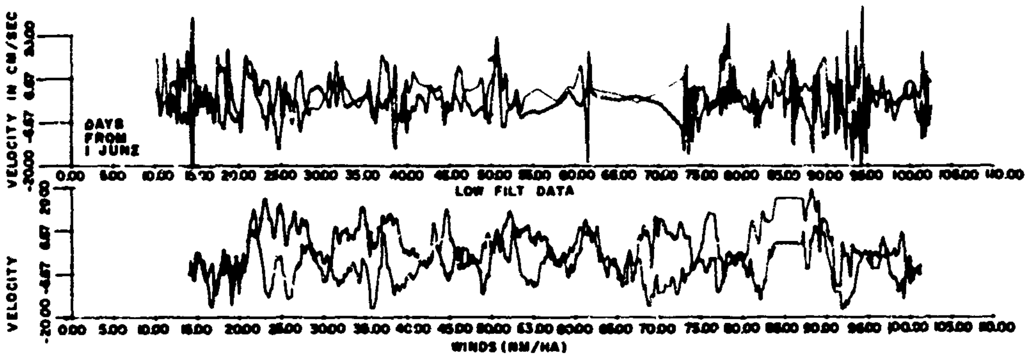

FIG. 7. Upper: U (light line) and V (heavy line with crosses) components of T-3 drift, from which oscillations with periods longer than 10 days have been subtracted. Lower: three-hour averages of winds recorded on T-3. U and V components marked as above.

The island motion and the local wind regime do not seem to be particularly related (Fig. 7), at least over short periods of time. This result is similar to analyses I had done previously (unpublished) which showed little correlation between ice station drift and winds for periods up to one week. On the other hand, Hunkins (personal communication) reported he has had some success in correlating drift and wind. Undoubtedly, the average large-scale ice drift patterns are wind-driven, but a detailed understanding of the coupling between ice and wind, sufficient for forecasting ice movement, awaits much more extensive research.

A preliminary feeling for the water motion measured under T-3 may be had from Fig. 8. Here are plotted the relative currents (U and V components) at 3 levels, 150 m. (in the pycnocline), 500 m. (core of Atlantic layer) and 1300 m. (in the bottom water), for a portion of the record. The following points may be noted:

1) The flow is quite similar in the three water masses. Since there is little shear in the water column, the dominant mode of motion is barotropic;

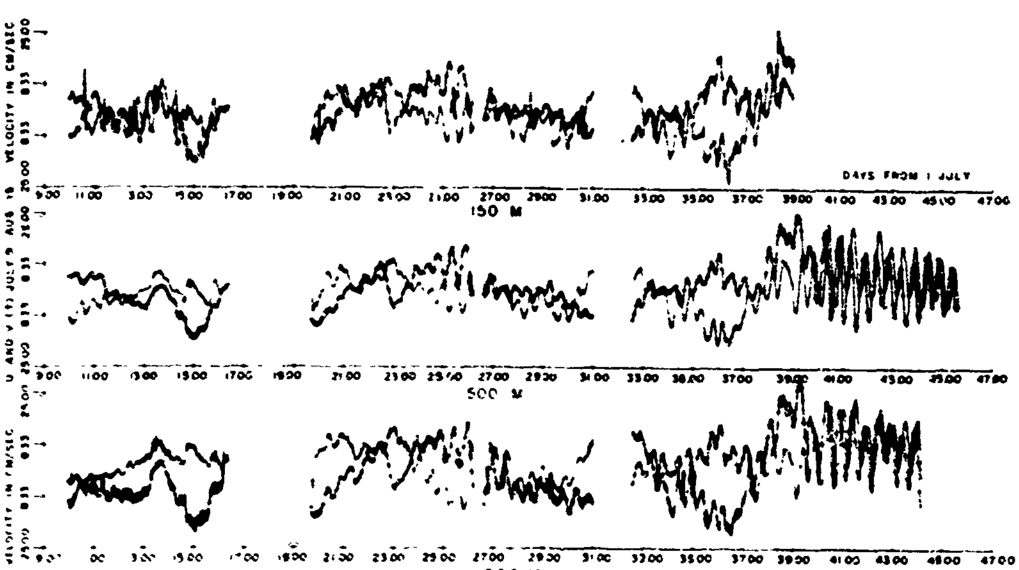

FIG. 8. Relative currents recorded under T-3 at three depths between 9 July and 15 August 1967. U (line) and V (line with +) are three-hour averages of the 10-minute recordings.

2) Island motion would also be reflected in the record because these are relative measurements. There is a long-term period variation in this record, a period of 2 to 3 weeks, which is probably the island motion noted above;

3) There is a very marked oscillation of approximately semidiurnal period. The phase shift between U and V of approximately 60° indicates cum sole rotation; we are undoubtedly measuring an inertial or semidiurnal tidal oscillation in the water, and it would appear that this wave provides the dominant magnitudes of flow, ±⅓ knot.

We now have similar current records from 1968 and 1969 to analyse. However, a more thorough analysis of these records plus many more will be required before we can say very much about the flow regime obtaining in the Arctic Ocean. The regime is complex, as with all of the World Ocean, and we have a variety of periodic and aperiodic phenomena to contend with. It is clear, though, that our techniques, reliable recording current meters together with frequent satellite navigation fixes, are finally producing data from which some progress can be made in describing the water motions and variations.

PHYSICAL OCEANOGRAPHY INTO THE FUTURE

The principal physical oceanographic problems in the Arctic Ocean may be summarized:

1) The ice and water motions and variations, and relation to the driving forces. Here are included questions about the frictional coupling between ice and water, how the ice cover deforms under the normal stress field, and the movement of the Atlantic and bottom waters; and

2) The exchange of heat with the atmosphere. Here are included questions about the role of leads vis-a-vis ice in heat-energy exchange across the surface, and how the heat from the Atlantic layer is passed upward through the Arctic water.

The survey stage of oceanography is essentially passed. Today, oceanographic field work should be undertaken as experiments to test hypotheses or models, for example, specific studies to attack aspects of the major problems outlined above. In our present efforts from T-3, where we are strictly limited geographically and synoptically, we try to concentrate on those experiments for which an "ice island without satellite station capability" (cf. Coachman 1968) is particularly suited.

Physical oceanography in the Arctic Ocean today is being conducted in a manner essentially the same as that of Nansen 70 years ago. That is, we still place a station in the ice cover and measure when convenient with Nansen bottle and reversing thermometer. In this same period of time, logistic and scientific hardware has been enormously improved. For example, the nuclear submarine and the C-130 aircraft for long range and quasi-synoptic operations, and helicopters, Otters and hovercraft for smaller-scale operations have all proved to be operable in the Arctic. Scientific instruments of improved accuracy such as the STD meter, recording current meters and satellite navigation devices have only begun to be used. The next step is the use to a greater extent of all the modern oceanographic and support equipment in the conduct of specific experiments.

The major observational gap, as indicated, is in spatial deployment of synoptic measurements. I propose a series of experiments, from simple to more complex, in which water properties and currents would be measured using the most modern equipment, and supported by the best modern equipment and technology. These experiments are aimed primarily at problem (1) above, but when meteorological and other observations are included they also provide information aimed at problem (2) above. The experiments are:

1) During summer 1969 pairs of recording current meters have been suspended from T-3 on opposite sides of the island, a separation of 5 km. A long-time series, together with as many satellite navigation fixes as possible, should allow definition of the spatial coherence of the currents on a horizontal scale of 5 km.;

2) The next larger scale of experiment, which was proposed for execution during spring in both 1968 and 1969 but has not been undertaken because of inadequate logistic support, we call the "geostrophic experiment." A triangular array of 3 temporary stations would be established at 15 km. distance around T-3, and supported and positioned by NARL Cessna aircraft. Recording current meters would be suspended under T-3, and at the satellite stations hydrographic casts would be made every 4 hours synoptically for a week or so. We should be able to estimate from the results the validity of the geostrophic approximation for Arctic Ocean currents; a similar experiment in other oceans would require four ships;

3) The next largest scale of experiment that has been proposed is an ice-deformation study, mentioned by Untersteiner (pp. 195-99). A triangular array of manned stations would be occupied for one month in the spring of 1970. T-3 would be one, with satellite navigation fixing capability, and the other two would be about 150 km. distant and within range of the precise position-fixing capability provided by the Polar Continental Shelf Project. Synoptic hydrographic and current measurements would be made from the stations;

4) The grand-scale experiment would be similar, but extended to cover the Arctic Ocean. Three to six manned stations, equipped with STD and recording current meters, would monitor the detailed time variations in water properties and currents. Additional spatial coverage could be obtained through unmanned stations; these could be positioned and the data remotely collected using the IRLS subsystem of the Nimbus satellite. Finally, synoptic surveys over the basin four times yearly would be achieved utilizing a nuclear submarine specifically equipped for the conduct of physical oceanographic measurements. Appropriate meteorological and other measurements would of course also be made. This experiment, even though expensive, would produce a more comprehensive picture of an ocean system at much less cost than can be envisaged for any other ocean.

ACKNOWLEDGEMENTS

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Arctic Geophysics

KENNETH HUNKINS[1]

The earliest geophysical studies at Point Barrow were conducted during the First International Polar Year, 1882-1883. Lieut. Ray of the U.S. Army Signal Corps established a station near the present Browerville primarily for the investigation of geomagnetic and auroral phenomena. Even at that early date, Point Barrow was the natural site for research in arctic geophysics by the United States. However, it was not until after the Second World War that geophysics became an important part of the research program at Barrow. The large-scale geophysical exploration of Naval Petroleum Reserve No. 4 focused interest on the area and was an important factor in the establishment of the Naval Arctic Research Laboratory. Barrow was the centre for exploration by gravity, magnetic and seismic methods which extended from the foothills of the Brooks Range to the shores of the Arctic Ocean (Woolson *et al.* 1962). An asymmetric sedimentary basin was found beneath the Arctic Coastal Plain. The axis of the basin strikes east-west, parallel to the Brooks Range and the coast. The deepest part of the basin is near its southern boundary where it abuts the thrust-block mountains of the Brooks Range. Cretaceous sedimentary rocks fill the basin to a depth of 5 to 7 km. along its axis. They thin northward and are only 500 m. thick at Point Barrow.

In the years following the exploration of Naval Petroleum Reserve 4, other geophysical studies were begun at NARL. Heat flow through the earth and the problems of permafrost received considerable attention through the fifties. A regional gravity survey of Alaska was made, revealing a large negative Bouguer anomaly over the Brooks Range (Woollard *et al* 1960). This survey was later extended seaward to cover much of the Chukchi Sea (Ostenso 1968b). The data indicate that an extension of the Brooks Range continues beneath the Chukchi Sea and joins with the Chukchi-Anadyr fold belt of Siberia. NARL serves as a magnetic and seismological observatory as well as a base for field operations. The U.S. Coast and Geodetic Survey continuously monitors the earth's magnetic field there and an earthquake seismograph station has recently been installed.

At Barrow, one looks northward across the Arctic Ocean stretching, without interruption, to Europe and the Atlantic Ocean. It was natural to consider research programs in marine geophysics as a goal for NARL. This goal began to be realized in 1960 when Arctic Research Laboratory Ice Station I (ARLIS I) was established. Although there was no geophysical program on ARLIS I the experience gained led to ARLIS II in 1961 on which was established a program in marine geology and geophysics.

ARLIS II was in operation for four years, drifting the length of the Arctic Ocean before leaving in the East Greenland Current. It was finally evacuated in Denmark

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Strait in 1965 shortly before it disintegrated and melted. Precision depth, magnetic, seismic reflection and navigation data were collected by a Lamont-Doherty Geological Observatory party during the first two years of the drift. A University of Wisconsin group made gravity observations throughout the four years and operated a seismic profiler during the last three years.

During 1961 and 1962, ARLIS II drifted over the basin between the Lomonosov Ridge and the Alpha Cordillera. The results have been reported by Kutschale (1966). The Wrangel Abyssal Plain was particularly well studied and found to be underlain by at least 3.5 km. of nearly horizontal, stratified sediments. A bedrock dam trapped sediments in this basin until it was filled to the sill depth. They then flowed over the top into a deeper part of the basin floored with the Siberia Abyssal Plain. The present surface of the Wrangel Abyssal Plain is cut by channels which funnel sediments through the Arlis Gap which joins the two abyssal plains. Crustal models based on gravity, magnetic and seismic reflection measurements indicate a crustal thickness of 15 km. beneath the Wrangel Abyssal Plain and 22 km. beneath the buried basement ridge (Figs. 1 and 2).

About 2,400 km. of sub-bottom reflection profiles off the east coast of Greenland were obtained from ARLIS II by the University of Wisconsin team with a sonar boomer system (Ostenso 1968a). Three widely separated faults were discovered on the Greenland shelf. These features were correlated with known faults on land, extending knowledge of Caledonian tectonics into the ocean. The Jan Mayen fracture zone of the Mid-Atlantic Ridge was also shown to extend onto the continental shelf.

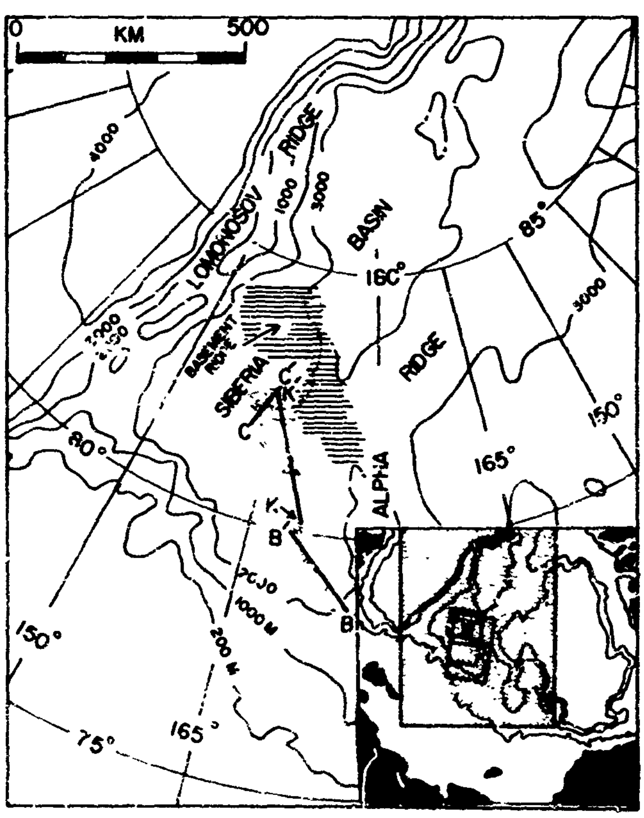

FIG. 1. Bathymetric map of portion of the Arctic Ocean investigated during ARLIS II drift of 1962 (Kutschale 1966).

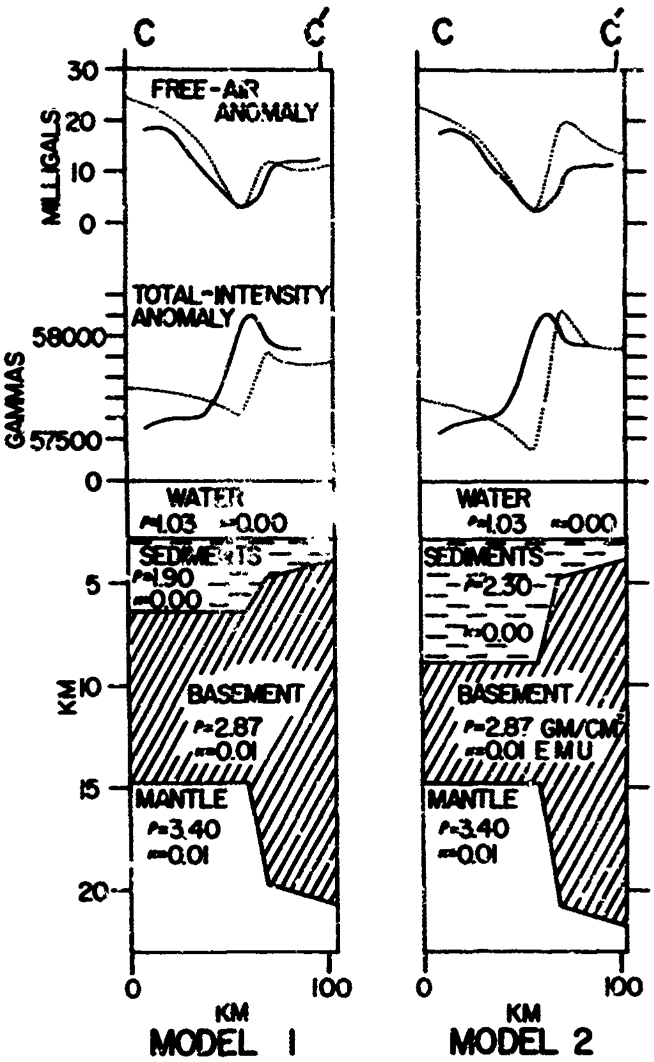

FIG. 2. Comparison of measured (solid curve) and computed (dotted curve) free-air gravity anomalies and total-intensity magnetic anomalies along section C-C' of Fig. 1. Vertical exaggeration 10:1 (Kutschale 1966).

In addition to this type of continuous geophysical profiling which is conducted at drifting stations, special geophysical experiments are often run. The first measurements of seismic noise on the Arctic Ocean floor were made from ARLIS II in 1962 (Prentiss and Ewing 1963; Prentiss *et al.* 1965). A seismometer was successfully operated on the ocean floor for short periods. The data were telemetered to the surface by means of an acoustic link. Acoustic noise measurements in the 0.1 to 100 hz. band were also made on the ice surface at the same time.

Lower frequency waves, essentially modified gravity waves rather than acoustic waves, were also studied at ARLIS II (Hunkins 1962; LeSchack and Haubrich 1964). These long waves are interpreted as ocean swell modified by the influence of the pack ice. Observations were made primarily with gravity meters. Simultaneous measurements with two instruments at different locations showed the waves to be progressive. Wave amplitudes are on the order of a millimeter at periods of 10 to 100 seconds and are imperceptible except with instruments. Amplitudes generally increase with period throughout the observed range.

Seismic studies of ice island ARLIS II itself were made in 1961 to determine its thickness and elastic properties (Kutschale 1968). The ice island was roughly rectangular in shape, measuring about 6½ by 3 km. The ice island, presumably a remnant of a broken ice shelf, was composed of two ice types: a debris-rich gray glacial ice and a stratified blue sea ice. Seismic measurements, levelling and coring all showed the gray glacial ice to be about 25 m. thick whereas the blue sea ice varied from 6 to 14 m. in thickness.

Fletcher's Ice Island, T-3, has been occupied as a NARL drifting research station since 1962. T-3 had previously been used as a drifting research station by the U.S. Air Force. In April 1960 the ice island became grounded on the continental shelf 80 miles northwest of Barrow. A stationary base so close to Barrow held little interest for researchers and it was abandoned in September 1961. Sometime during the following winter T-3 drifted free and was spotted on 16 February 1962 from an ARL airplane on a routine supply flight to ARLIS II. The station was occupied a few days later and by May of that year a geophysical program was being conducted by Lamont. Navigation, depth, magnetic and gravity fields were monitored. This basic program, with many improvements, is still in operation.

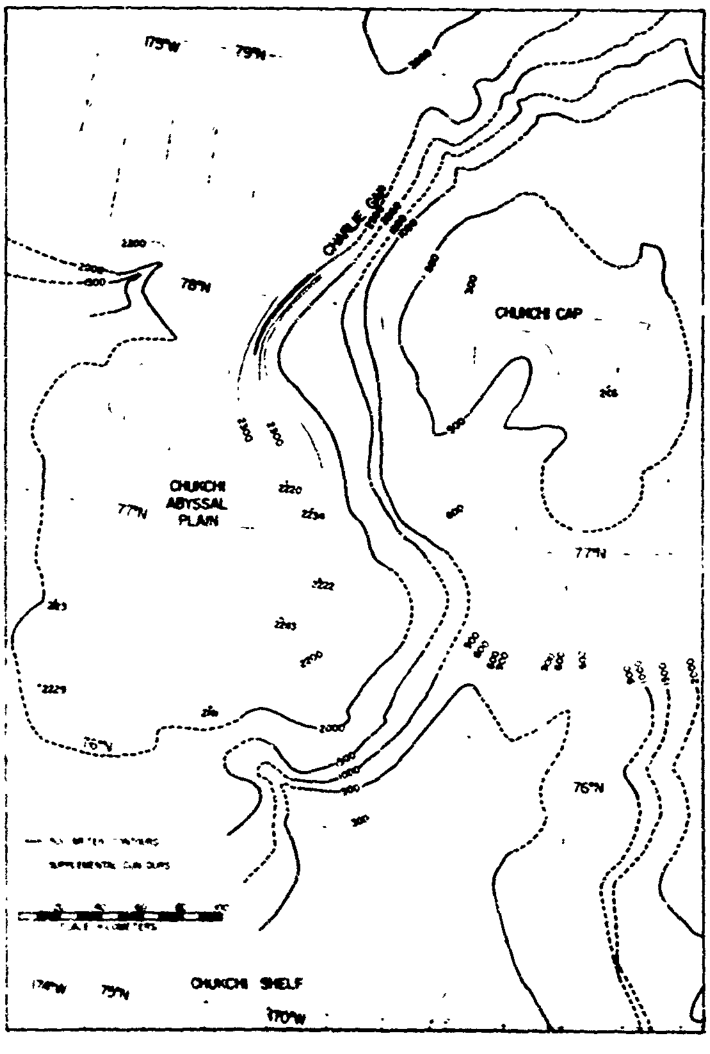

FIG. 3. Bathymetric sketch of the Chukchi Cap and Chukchi Abyssal Plain (Shaver and Hunkins 1964).

During the summer of 1962, T-3 crossed the Chukchi Cap, a marginal plateau about 150 km. in diameter. The topography of this feature (Fig. 3) was further explored and the large magnetic anomaly on its western flank was delineated more clearly. The Chukchi Cap is apparently a continental fragment which has been broken from the Alaskan continental shelf (Shaver and Hunkins 1964).

Drifting ice stations are stable platforms which can be used for experiments which are not feasible in other oceans. In October 1962, a proton-precession magnetometer with two sensing heads was installed at T-3 (Heirtzler 1967). One head was at the surface and one was suspended at a depth of 330 m. to form a vertical gradiometer. This configuration allowed magnetic anomalies to be de-

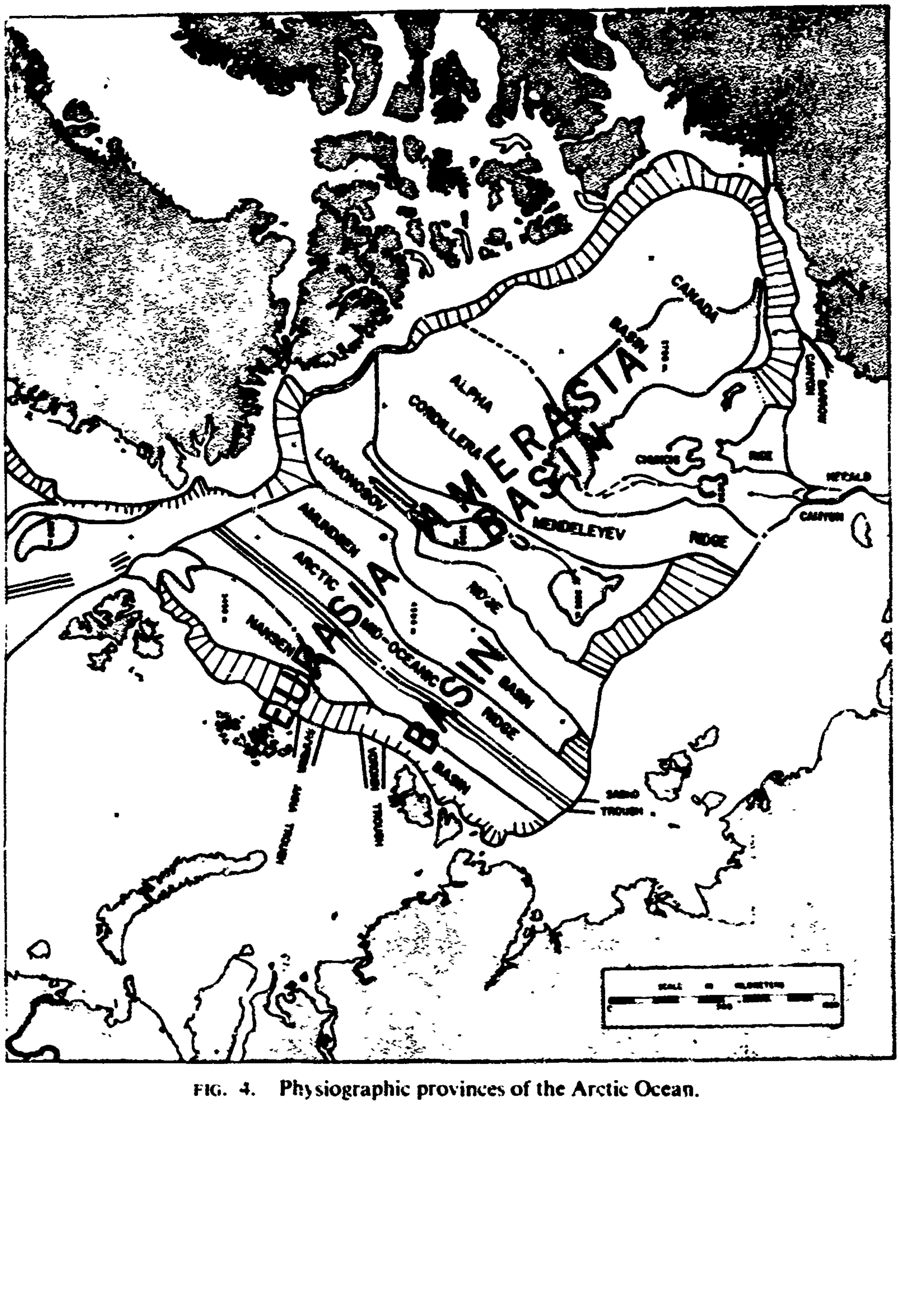

FIG. 4. Physiographic provinces of the Arctic Ocean.

tected in the presence of large time variations of the magnetic field. The observations showed a small but measurable attenuation and phase lag at the lower sensor in the 90 to 400 sec. period range. This however did not limit the use of the gradiometer for defining crustal anomalies.

A Precision Depth Recorder has operated nearly continuously at T-3 since 1963. Records from this instrument show details of bottom texture necessary for understanding sedimentary processes on the ocean floor. Deep-sea channels and abyssal plains, for example, can only be adequately resolved with the PDR. Soundings made from T-3, as well as from other drifting stations and nuclear submarines, have been essential in forming present concepts of Arctic Ocean shape and structure.

Present bathymetric knowledge of the Arctic Ocean is summarized by Beal (1968), Hunkins (1963) and de Leeuw (1967). The outlines of recognized physiographic provinces are shown in Fig. 4. Three major ridge systems cross the basin with their axes nearly parallel to each other. Each of the three ridges has its own distinctive characteristics.

The Alpha Cordillera is broadly arch-shaped in profile. The topographic texture is rough and the cordillera appears to be composed of many smaller ranges. It is about 1000 km. in width and stands 2 km. above adjacent ocean basins. It is not seismically active but has a rough magnetic texture.

The Lomonosov Ridge contrasts with the Alpha Cordillera in shape, texture and magnetic field. The Lomonosov Ridge is only 60 to 200 km. wide and has a smooth, asymmetric profile. No appreciable magnetic anomaly is found over this ridge. Like the Alpha Cordillera, it is aseismic.

The Arctic Mid-Ocean Ridge, however, is seismically active, being an extension of the Mid-Atlantic Ridge into the Arctic Ocean. The term Arctic Mid-Ocean Ridge, although it indicates the continuity between this ridge and the world-wide mid-ocean ridge system, is not quite accurate for it is located near one side of the Arctic Basin rather than in the middle. The seismic epicenters are located beneath the crest of the ridge, coinciding, as nearly as can be determined, with the rift valley which forms a cleft along the crest.

Each of these ridges plays a role in current theories of the origin of the Arctic Basin. The concept of ocean floor spreading has proved fruitful in other oceans and can be applied to the Arctic Ocean. The concept calls for movement of the ocean floor away from the ridge at a rate of a few centimetres per year. The line of rifting and seismicity marks the present locus of spreading. Mantle derivatives are introduced from below along the rift valley to form new oceanic crust.

Sea floor spreading is believed to be taking place in the Arctic Ocean at present along the Arctic Mid-Ocean Ridge. The rifting apparently split off the outer edge of the continental shelf which now forms the Lomonosov Ridge. The smooth topography of this ridge, and the match between the shelf and the Lomonosov Ridge outlines tend to support this idea.

This accounts for the origin of the Eurasia Basin but leaves the origin of the Amerasia Basin still to be explained. It has been speculated that the Amerasia Basin was also formed by rifting but at an earlier date. The Alpha Cordillera, according to this hypothesis, is an inactive mid-ocean ridge which has stopped spreading. The present evidence for the Alpha Cordillera as an extinct mid-ocean ridge is based on bathymetric, magnetic and heat flow data. However the support is still weak, and more geophysical data are needed to decide the merit of the concept.

Crustal structure in the Arctic Ocean can only be better understood if field expeditions are mounted to examine present theories. Surveys should be designed to test whether the Lomonosov Ridge is a continental shelf fragment and whether the Alpha Cordillera is an ancient locus of spreading. This will require detailed aeromagnetic flights, seismic reflection and refraction surveys as well as new tools which are still to be developed. One of the essential requirements for this work is a flexible transportation system including single- and multi-engine airplanes, helicopters, and hovercraft, operating from permanent as well as temporary ice stations. Drifting ice stations have made major contributions to Arctic Ocean geophysics but the scope of manoeuvres must now be widened if the interesting problems posed by new theories of ocean basin origins are to be solved.

ACKNOWLEDGEMENT

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Paleoecology and Sedimentation in Part of the Arctic Basin

DAVID L. CLARK[1]

INTRODUCTION

The Arctic Basin occupies an area of approximately 10 million sq. km. Information available suggests that the number of sediment cores taken from the Arctic Ocean by all students of the area is of the magnitude of one for every 10,000 sq. km. and these have not been uniformly spaced. The amount of detail provided by such coverage is not impressive to the geologist who may be accustomed to working with continual sediment sections along a mountain front or from wells which have been drilled at 10- to 20-mile intervals into the earth's sediment crust.

Most of the 1,000 or so sediment cores which have been taken from the Arctic Ocean floor are less than 4 m. long. Our best age determinations show that these cores provide little more than a million or a million and a half years of the sediment record. Thus the argument that we know very little concerning arctic paleoecology based on sediment studies is well founded.

HISTORY

The history of sedimentologic and resulting paleoecologic interpretations of the Arctic Basin can be divided quite easily into three parts. The first part is that interval of work, largely Russian, which was involved with sediment studies of the arctic coastal areas and rivers. This work extended from early in this century to about 1950; it was conducted from ground and shipboard stations and largely involved grab samples of surface sediment. One exception was work done on the Russian drifting station North Pole 1 which consisted of sampling the upper 20 cm. of sediment during 1937-38 (Androsova 1962). Emery (1949) summarized much of the Russian data for the Arctic and the first three volumes of the *Arctic Bibliography* (Tremaine 1953) neatly tabulate most of the sediment studies for this period.

The second chapter of sedimentologic work in the Arctic is that of the Russians during the past 20 years. This work has been done in many parts of the Russian Arctic as well as from more seaward parts of the Arctic Ocean. Shipboard work along coastal areas and from drifting ice islands has provided considerable data on surface sediments. In addition, and especially important for paleoecologic work, short sediment cores have been recovered and studied. Belov and Lapina (1959) summarized a study of 450 cores whose average length was 100 to 150 cm. These were taken from ice islands in the central Arctic Ocean. By 1950,

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more than 500 cores had been collected. From these cores, the distribution of sediment types and some microfaunal data were obtained (Belov and Lapina, 1962). Longer cores, some 6 m. long, were taken as some of 500 bottom samples collected from the central, eastern and southern parts of the Bering Sea (Gershanovich 1962). More recently, Linkova (1965) has reported some details of sediment study from short cores taken from the Lomonosov Ridge. Ignatius (1961) reported on 41 one to three metre cores taken in the Barents Sea.

These studies and others which were based only on surface samples have furnished isolated facts on chemical, mineralogic, petrographic and faunal patterns for an enormous area. The data are still too few and the intervals of "no data" too large to give much more than a hint of the kind of comprehensive survey which is needed for the Arctic.

The third chapter of sediment study in the Arctic is a brief one and based mainly on the work of North Americans. Much of this has been sponsored by the United States and supported by NARL. This includes the Beaufort Sea studies of 1950 and 1951 during which 179 bottom samples were taken (Carsola *et al.* 1961), the U.S. Air Force Studies on T-3 (1959), the Kara Sea studies of the mid 1960's (Andrew and Kravitz 1968), and the Chukchi Sea studies (Creager and McManus 1961). Some of the other important studies include the work of Cromie (1960) who reported on 22 short cores taken from the drift station Charlie across the Chukchi Shelf, a study of 58 cores from the Arctic Ocean and 26 cores from the Greenland and Norwegian Seas by Ericson and others (1964), a study of cores from Baffin Bay by Marlowe (1966) and from the Alpha Cordillera by Herman (1964).

The Lamont Group, particularly K. Hunkins, has published a variety of small studies including work on some spectacular gravels from the Alpha Cordillera (Schwarzacher and Hunkins 1961) and several summary papers for parts of the same area (Hunkins and Kutschale 1967; Ku and Broecker 1967).

The data reported by these investigators and others are diverse and no important patterns of sedimentation or paleoecologic conclusions have been drawn from the reports. It is important to note that the early work involved bottom samples, not cores, but work from drifting ice masses during the past 30 years has facilitated recovery of hundreds of cores from many parts of the Arctic Ocean. Study of the cores will provide the framework for a thorough paleoecologic understanding of the Arctic Basin. Hopefully, new stations can be established in the Eurasia Basin so that "complete" coverage will be possible.

PRESENT STUDIES

To date, more than 300 sediment cores have been taken during the drift of T-3. After heat flow studies by Lachenbruch and Marshall on T-3 and sample examination in California, cores are sent to our laboratories at the University of Wisconsin in Madison Throughout March 1969, more than 80 cores were received in Madison. Some 50 cores have been studied, the detail ranging from mineralogic analysis of top and bottom segments to a sediment, mineralogic and faunal study of every segment of some cores. Most of the cores for which we now have data

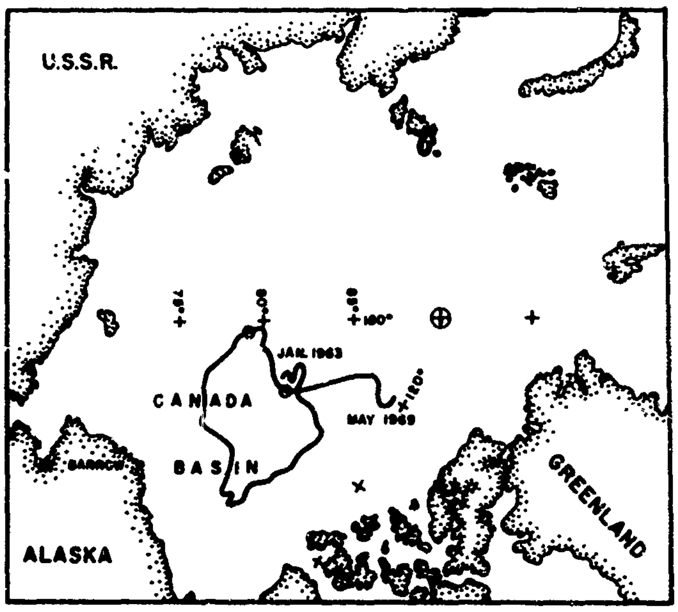

FIG. 1. Traverse of T-3 in Arctic Basin from 1963 to April 1969.

can be grouped as Canada Basin area cores or Alpha Cordillera area cores (Beal *et al.* 1966). Since 1963, T-3 has drifted from just off of the Alpha Cordillera, south the length of the Canada Basin, across the Chukchi Rise-Plateau, through the Charlie Gap, north to the Alpha Cordillera and now south, along the eastern edge of the Canada Basin (Fig. 1).

The study is in the data-gathering stage and only a few conclusions have been drawn from a mass of data. This report is a preliminary statement on our progress.

PROCEDURE

Cores are received in approximately 15 cm. segments. Samples for magnetic determinations are taken at approximately 5 cm. intervals in each segment. The remaining part of the sampled half-core is divided into portions for use in sedimentologic and faunal studies. Moisture content is determined for sub-portions of each segment and X-ray diffractograms are made for at least the top and bottom segment of each core. Samples are washed through a 250-mesh screen. Material passing through the screen is defined as "fine" and that caught on the screen is defined as "coarse." The percentage of coarse fraction for each sample is determined and studied for clastic and faunal components. The percentage of each is computed. To date, data for 50 cores have been determined. Present investigations are directed toward as complete a study as possible for top and bottom segments of every core. In addition, magnetic determinations and moisture and textural data are gathered for every segment of every core.

MAGNETIC STRATIGRAPHY AND RATES OF SEDIMENTATION

The most recent major reversal of the earth's magnetic field has left a good record in most of the cores which are 2½ m. long or longer (Fig. 2). The polarity

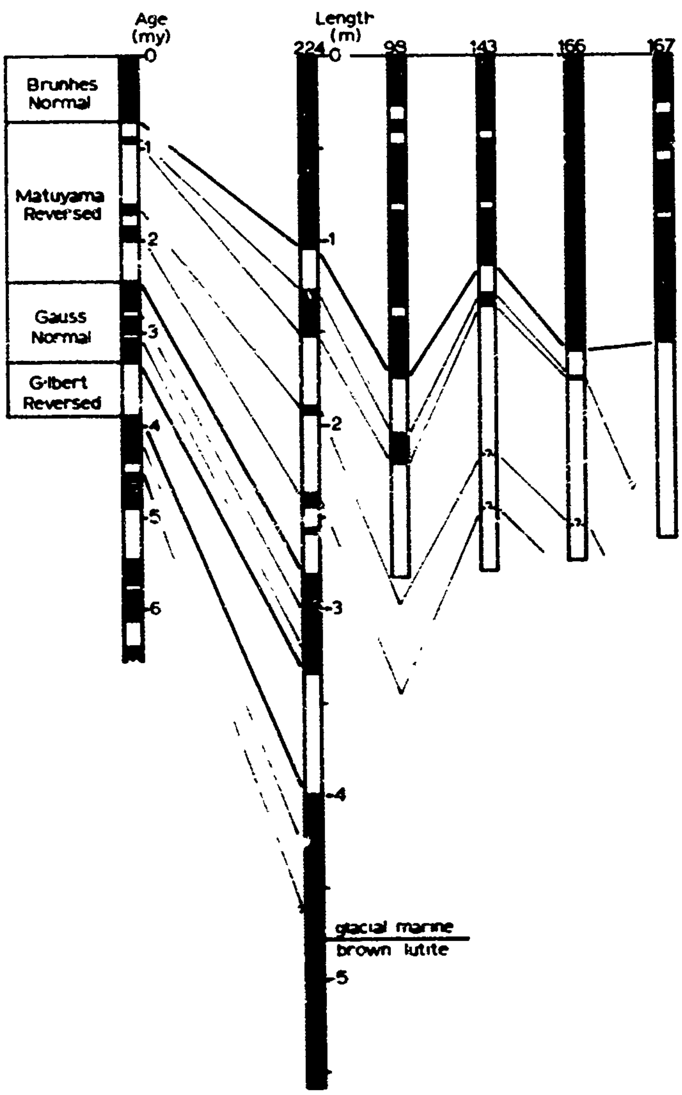

FIG 2. Magnetic stratigraphy and correlation of 5 cores from Canada Basin area (after Steuerwald *et al.* 1968).

change in the Arctic can be correlated with magnetic stratigraphy determined in other parts of the world (e. g. Cox *et al.* 1964; Opdyke *et al.* 1966; Hays and Opdyke 1967). Cores longer than 3 m. show the record of more numerous magnetic events. Core 224, for example, from 80°N., 1 8°W., is 5-6 m. long and may be correlated with magnetic events of the past 4 million years (Steuerwald *et al.* 1968).

The most recent major magnetic reversal (beginning of the Brunhes Normal) has been determined to be approximately 700,000 B.P. on the basis of varied radiometric measurements (Cox 1968); it has been found to occur between 100 and 200 cm. in many arctic cores. This fortuitous occurrence provides a very useful time line for a variety of studies. For example, using the assumption of a uniform rate of sedimentation and the time determination provided by the Brunhes polarity reversal, we have calculated apparent sedimentation rates of 1 to 3 mm. per 1,000 years for parts of the Arctic Basin. The highest rates of sedimentation have been found in the Canada Basin (Canada Plain area). There, cores taken in the 80°N. area show minimum sedimentation rates of greater than 3 mm. per 1,000 years. In the 75°N. part of the Canada Basin, minimum rates of 2 to 3 mm. per 1,000 years have been found. Bathymetric data here show depths in excess of 3,600 m. and the high sedimentation rates are due, in part, to density flows which have been noted in cores from this area.

In contrast, cores from the Chukchi Plateau-Plain area have sedimentation rates of 1 to 2 mm. per 1,000 years. Water depths here are less than 2,000 m. or only one half as deep as the Canada Basin. Also, the Chukchi area contains sediment which apparently is free of density flows.

MOISTURE CONTENT

The percentage of moisture by weight for several intervals of each segment of each core studied was calculated. Moisture content is commonly but not always higher in the uppermost or surface sample. The percentages for each interval of the cores were plotted but no pattern of increase or decrease of moisture content with depth was apparent. The percentages range from 30 to 55 throughout the cores. However these data may be too few or post-coring treament of the cores may be too unstable for meaningful results.

GROSS MINERALOGY

X-ray diffractograms have been prepared for every segment of 10 cores and for the top and bottom segments of 50 cores. The cores all contain approximately 15 to 25 per cent kaolinite, 15 to 25 per cent illite, 20 to 40 per cent quartz, and less than 10 per cent chlorite. The amounts of dolomite, calcite and feldspar tend to range more spectacularly than the clays or quartz, however. These three components were plotted on a triangular grid and some geographic pattern of mineralogy was apparent.

Windom (1969, p. 776) has provided significant data on the <2 micron clay mineralogy of dust from Greenland ice and has compared this to Arctic Ocean sediment. The kaolinite and chlorite percentages show some correlation with our percentages. Most interesting is Windom's conclusion that atmospheric dust may accumulate at rates of 1 mm. per 1,000 years. If this figure is valid for the Arctic, all or a considerable percentage of the total "fine" sediment which has accumulated in the Arctic, is of atmospheric origin.

Cores in the northern part of the Canada Basin have surface concentrations of dolomite and calcite in approximately equal parts. Lesser amounts of feldspar are present. In this same area the feldspar increases in relation to calcite and dolomite with depth in the cores.

In the central and southern parts of the Canada Basin, calcite concentration is nearly equal to that of dolomite and feldspar in surface samples but with depth the calcite shows a relative decrease compared to dolomite and feldspar.

The Chukchi area cores are more variable. In some cores the surface material is primarily dolomite and feldspar and in others calcite is present in amounts equal to the dolomite. In all surface samples feldspar predominates. In these cores there is either no change in relative amounts with depth or there is a relative increase in feldspar with depth.

Clearly, these data provide little more than a hint of patterns of mineral distribution. Smaller-scale studies on diagenesis or authigenic minerals or trace element distribution which are planned may reveal more significant mineralogic patterns.

CARBONATE CONTENT

The total carbonate percentage of samples was determined by solution studies (Table 1). In the Canada Basin area, both tops and bottoms of cores have carbonate contents ranging from 7 to 28 per cent. In the Chukchi region, carbonate contents range from 9 to 16 per cent. In the northern part of the Canada Basin there is a general decrease in percentage of carbonate from the top segment to the bottom segment of 3-m. cores. For example, 14 per cent to 7 per cent, 26 to 7 per cent, 28 to 9 per cent, 24 to 14 per cent and 11 to 9 per cent are averages from top segments to bottom segments in 5 cores. In the southern part of the Canada Basin (75°N.) there is a general increase of carbonate with depth (11 to 15 per cent, 11 to 20 per cent, 11 to 28 per cent, 13 to 19 per cent, 17 to 20 per cent) but there are exceptions to this trend in this area too. In general, both parts of the Canada Basin have low numbers of Foraminifera but at least two of the cores from the Canada Basin have relatively numerous forms.

In the shallower Chukchi Plateau area, both increase and decrease of carbonate with depth was noted. All of these figures show some correlation with the X-ray data.

TABLE 1. Carbonate content of surface segment and bottom segment of selected cores*.

	Depth (m.)	(surface) % Carbonate	(bottom) % Carbonate
Northern Canada Basin	2245	14.0	7.9
	2213	26.5	7.2
	3415	28.5	9.6
	3492	24.6	14.2
	3746	11.1	9.5
	3741	11.0	15.8
	3757	11.9	8.6
	3695	11.0	20.2
	3672	14.0	13.5
Southern Canada Basin	3680	11.3	15.1
	3677	11.0	20.9
	3677	11.8	28.2
	3665	13.4	19.1
	3613	17.2	20.6
Chukchi Plateau	1564	14.4	8.0
	1845	9.0	13.4
	1870	16.3	7.7

*Based on weight loss due to treatment in 10% HCl.

TEXTURE ANALYSIS

Coarse or fine, by our definition, is sediment larger or smaller than 61 microns. The fine material is a remarkably uniform lutite. The coarse material consists primarily of Foraminifera tests and clastic particles. Almost every core has at some point at least one larger pebble. Some of these are striated and apparently were deposited from melting glacial ice which rafted these erratics to their site of deposition. Most of the erratics are carbonate.

Brown lutite is the dominant sediment type in the Chukchi area and 5 to 16 per cent of the sediment by weight is composed of coarse material. The Foraminifera fauna ranges from 30 to 90 per cent of the coarse fraction by weight.

In the Canada Basin, the coarse fraction of any sample is 1 to 3 per cent of the total. Generally, faunal elements comprise a smaller percentage of the coarse than in shallower waters. A gray colour predominates.

MICROFAUNA DISTRIBUTION

Some 30 species of Foraminifera have been identified. All, apparently, are benthonic with the exception of *Globigerina pachyderma*. No nannoplankton or radiolarians have yet been identified. Cores from all areas of the Arctic which have been studied have a greater microfaunal percentage in the upper segments than in the lower.

Foraminifera are much less frequent in the sediments of the Canada Plain than in the cores from other parts of the Canada Basin or shallower areas. Commonly, in the Chukchi area 30 to 90 per cent of the total coarse fraction (from 5 to 16 percent of each segment) is Foraminifera. Foraminifera in the Canada Basin samples comprise 0 to 80 per cent of the coarse fraction which is 1 to 3 per cent of each segment.

Different faunal realms are apparent but are not understood yet. Arenaceous Foraminifera are common in the Canada Basin but uncommon in shallower parts of the Arctic. *Globigerina pachyderma* is the dominant species in all samples and comprises up to 100 per cent of the fauna of some samples.

The *G. pachyderma* fauna provides a range of possible studies. The coiling direction of specimens and its relationship to water temperature is one. Another is a study of the ratio of young to mature individuals and their distribution in the various bathymetric provinces. Paleoecologic interpretations from these data as well as the composition of the benthonic Foraminifera and related ecologic parameters is a major area of investigation.

SOME PALEOECOLOGIC CONCLUSIONS

Climatic Change

It has been suggested that sediment of the glacial and interglacial periods may be identified on the basis of quantity of planktonic Foraminifera and ice-rafted debris found in Arctic Ocean cores (Ericson 1964). An abundance of *Globigerina pachyderma* with abundant ice-rafted material should indicate relatively open, ice-free conditions, according to this idea. The arctic cores show pronounced fluctuations in abundance of *G. pachyderma* and coarse detritus. In some cores there is a general parallelism of these factors but in others, some closely spaced, there is no correlation. A high percentage of coarse content in a particular sample was often due to a high percentage of Foraminifera tests only. Rarely, a high percentage of coarse material was found to be due to high faunal and high clastic content. A regression graph of per cent detritus versus per cent fauna for several cores showed little relationship (Steuerwald *et al.* 1968).

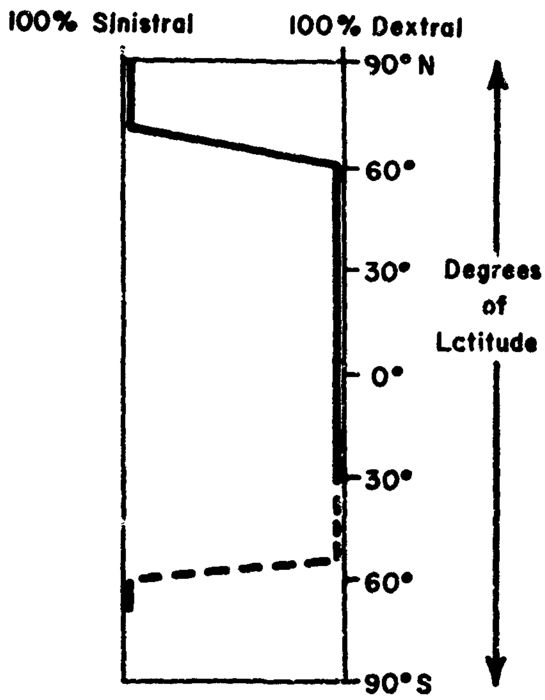

FIG. 3. Direction of coiling of *Globigerina pachyderma* and its relationship to latitude (after Bandy 1960).

A more interesting attempt at climatic interpretation has been made by tabulation of the sinistral or dextral coiling patterns of *G. pachyderma* (Steuerwald *et al.* 1968, Fig. 4). Various students have demonstrated that the present distribution of sinistral coiled *G. pachyderma* is related to water temperature (Bandy 1960; Ericson 1959). Present distribution of *G. pachyderma* as well as the distribution of this species during the Pleistocene is such that greater than 70 per cent of the population have sinistrally-coiled tests in cold water or during time of colder water (Bandy 1960), (Figs. 3 and 4). Relatively warmer waters support populations in which 90 to 100 per cent are coiled dextrally. Sinistral coiling forms were found to be dominant throughout several cores, usually at greater than 90 per cent. The only sustained trend noted throughout the core segments was toward less sinistral coiling specimens at the tops of cores. This has been summarized as follows: "If the water temperature control for coiling is related to climate, this coiling trend suggests that the Arctic has not been warmer than at present for at least the last one and one half million years. Altogether, these data do not indicate the existence of an interglacial or glacial ice-free Arctic during a great part of the Pleistocene" (Steuerwald *et al.* 1968, p. 83).

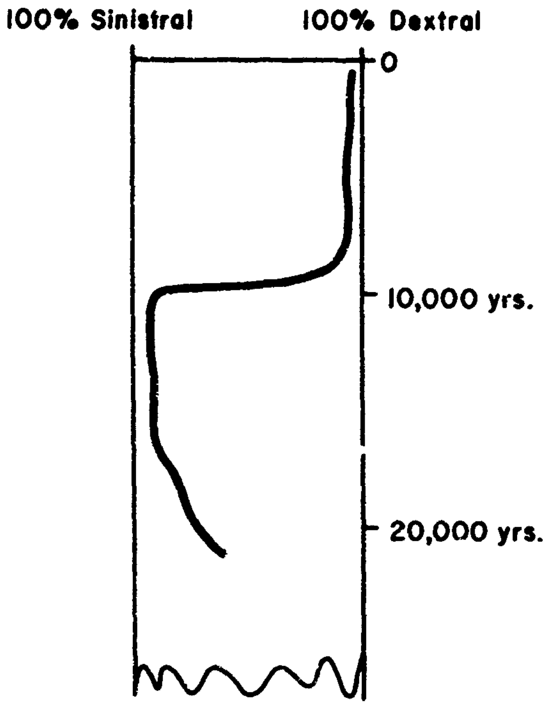

FIG. 4. Direction of coiling of *Globigerina pachyderma* and its relationship to time at 30° to 40° N. Composite section of cores from the Pacific off Southern California (after Bandy 1960).

Pollen data from terrestrial cores in several parts of Alaska have pointed to this same conclusion (Colinvaux 1964, 1967).

Magnetic Reversals and Faunal Change

It has been suggested that the removal of the magnetic shield associated with a reversal of the earth's magnetic field could be responsible for extinctions and/or rapid evolution of life. This idea that removal of the magnetic shield which, through the dual mechanism of sterilization and increased mutation, would be responsible for both the extinction of species and for the production of new species has been challenged (e. g. Black 1967). In the Arctic cores there is some correlation between times of magnetic reversals and faunal changes. Generally, there is a higher percentage of *Globigerina pachyderma* after the most recent reversal and correspondingly, there is generally a higher abundance of benthos below the most recent reversal. In all cores studied for this, there is an interval of few or no benthonic species at and following the magnetic reversal (Fig. 5) (Steuerwald *et al.* 1968). The specific composition changes little, however, and there is no indication of mass extinction of species such as has been noted in the Antarctic with radiolarians (Watkins and Goodell 1967).

Whether the correlation between faunal changes and times of magnetic reversals is fortuitous or a cause and effect relationship may be answerable from other paleoecologic data.

The Pleistocene in the Arctic

Several cores from approximately 80 N. on the eastern edge of the Canada Deep are 5 m. or longer. Magnetic stratigraphy of one of these indicates that the lower part of the core includes sediment which may be in excess of four million

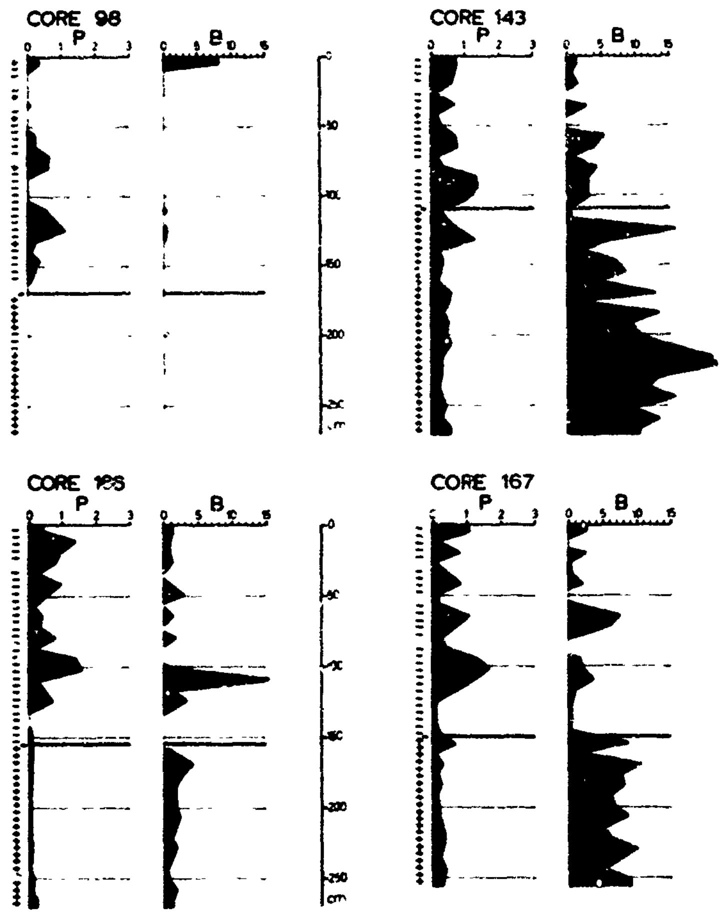

FIG. 5. Four cores from Canada Basin, their magnetic stratigraphy (+, —) and relationship of time of Brunnes reversal (heavy horizontal line) to percentages of planktonic (P) and benthonic (B) Foraminifera. (After Steuerwald *et al.* 1968).

years old. If so, the entire Pleistocene of the Arctic may be represented.

There is little sediment change throughout the core with the exception of a colour change near the base. This colour change occurs at an extrapolated age of approximately four and a half million years. Detailed faunal study of this core is in progress. Hopefully, this will furnish information on the paleoecology of the beginning of the Pleistocene in the Arctic.

FUTURE PALEOECOLOGIC STUDIES

Work up to the present has provided a foundation, even if insecure, on which significant paleoecologic research may progress. Promising lines of investigation in the next few years include:

1) Magnetic stratigraphy of the Arctic Ocean,
2) Oxygen isotope history of the Arctic Ocean,
3) Detailed microfauna studies,
4) Sediment dispersal pattern studies.

One of the most powerful new tools for ocean sediment studies is the spinner magnetometer. The widespread recognition of rather precise times of reversals of the earth's magnetic field and their confirmation in terrestrial and marine rock has provided paleoecologists with excellent time planes for their studies. A magnetic stratigraphy for the entire Arctic Basin can be determined. The time points thus provided will permit correlation of events which is more precise than techniques used in conventional terrestrial stratigraphic studies. It will be possible to reconstruct a detailed history of the Arctic Ocean including precise rates of sedimentation and times and duration of ecologic and climatic changes. The only limit on a thorough understanding of times and rates of the evolution of the Arctic Basin is the limitation on length of cores which can be taken. Additional stations are needed in the "unknown" parts of the Arctic Basin to provide a comprehensive picture.

The oxygen ($O^{18}:O^{16}$) ratios from Foraminifera tests provide determinations of paleotemperatures, paleosalinities and, indirectly, such factors as run-off, evaporation and vertical mixing of water in the Arctic during the geologic past (Craig and Gordon 1965; Van Donk and Mathieu, *in press*). The wealth of data which may be obtained through such studies should be correlated with sediment and paleomagnetic data.

Much paleoecologic information is to be obtained from a study of the distribution and composition of benthonic Foraminifera, especially the fauna in the remote parts of the Arctic. Shell porosity of the planktonic *Globigerina pachyderma* may be another excellent climatic index (Bé 1968).

Sediment distribution in the Arctic Basin appears to be as diverse as the Arctic Basin differs topographically. The arctic ice drifts and deposits clastic material. Some sediment is transported by density currents. Trace element or other small-scale studies may be more significant for interpretation of sediment dispersal patterns than other studies to date.

ACKNOWLEDGEMENTS

Current investigations have been based on sediment cores taken by A. H. Lachenbruch and Vaughn Marshall from Fletcher's Ice Island, T-3, since 1963. Grateful acknowledgement for their help in the study is made. Graduate students at the University of Wisconsin, B. A. Steuerwald, John A. Larson, Dennis A. Darby, David S. Charlton and John A. Andrew, have guided the work to its present status. All of the studies have been supported by the Office of Naval Research under contract No. 0014-67-A-0238-0002.

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Arctic Hydroacoustics

HENRY KUTSCHALE[1]

INTRODUCTION

The two features peculiar to the polar environment that most strongly influence underwater sound are the permanent ice cover and the velocity structure in the water. Ice movement generates background noise and the ice modifies propagation, particularly at high frequencies, by scattering waves from the rough ice boundaries. Sound velocity is a function of temperature, salinity, and pressure. The relationship between these variables in the central Arctic Ocean is such that sound velocity is generally an increasing function of depth from the surface to the bottom. Such a velocity profile is found only in polar waters. The sound velocity structure is remarkably uniform both as a function of location and time of year. Sounds are transmitted to great ranges in this natural arctic waveguide or sound channel by upward refraction in the water and repeated reflection from the ice canopy. A two-pound explosion of TNT has been heard at ranges exceeding 1,100 km. (700 miles). The surface sound channel of the Arctic is the polar extension of the deep sound channel or SOFAR channel of the nonpolar oceans (Ewing and Worzel 1948), but the arctic signals are often quite different from those observed in the deep channel, largely because of the predominance of low-frequency waves in the Arctic. The arctic sound channel is of considerable importance to the Navy because of the possibility of long-range detection and communication. That ocean also provides an ideal test area for new concepts of signal detection and processing because of the easy access to the sound channel and the permanence of installations located on ice islands.

The purpose of this paper is to review our present knowledge of underwater sound obtained from experiments made aboard drifting ice stations in the central Arctic Ocean and to recommend future research in this field. I shall present a summary of the results of experiments made by Lamont-Doherty Geological Observatory of Columbia University; these results have been published by Kutschale (1961), Hunkins and Kutschale (1963), Hunkins (1965), Hunkins (1966), and Kutschale (1968). Many of our experiments were conducted in cooperation with the U.S. Navy Underwater Sound Laboratory, the Pacific Naval Laboratory of Canada, and AC Electronics Defense Research Laboratories of General Motors Corporation. Results by workers from these laboratories have been published by Marsh and Mellen (1963), Mellen and Marsh (1963), Milne (1964), Buck and Green (1964), and Buck (1968).

Drifting ice stations provide an ideal platform for research on underwater sound. These stable platforms over deep or shallow water are far removed from ship traffic and they provide a large surface area for detector arrays. Detectors

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may be either seismometers mounted on the ice or hydrophones suspended at shallow depths in the water. Measurements of background noise and scattering layers may be made over periods of many years as the station moves slowly under the influence of winds and currents. Experiments on propagation are commonly made between two drifting stations, or between a station and an icebreaker or an aircraft. The latter type of experiment is particularly suited to measure the range dependence of the sound field and to determine the effects of bottom topography on the propagation.

High explosives have been the principal sound sources for transmission experiments. These sources radiate high sound intensity over a broad frequency range and they are easy to launch. Offsetting these advantages are the change of source spectrum with shot depth at constant charge size, occasional partial detonations, and some variation of firing depth for pressure-activated charges dropped from an aircraft. Also, detailed comparison of theoretical computations with measurements are often far more difficult than for constant frequency sound sources.

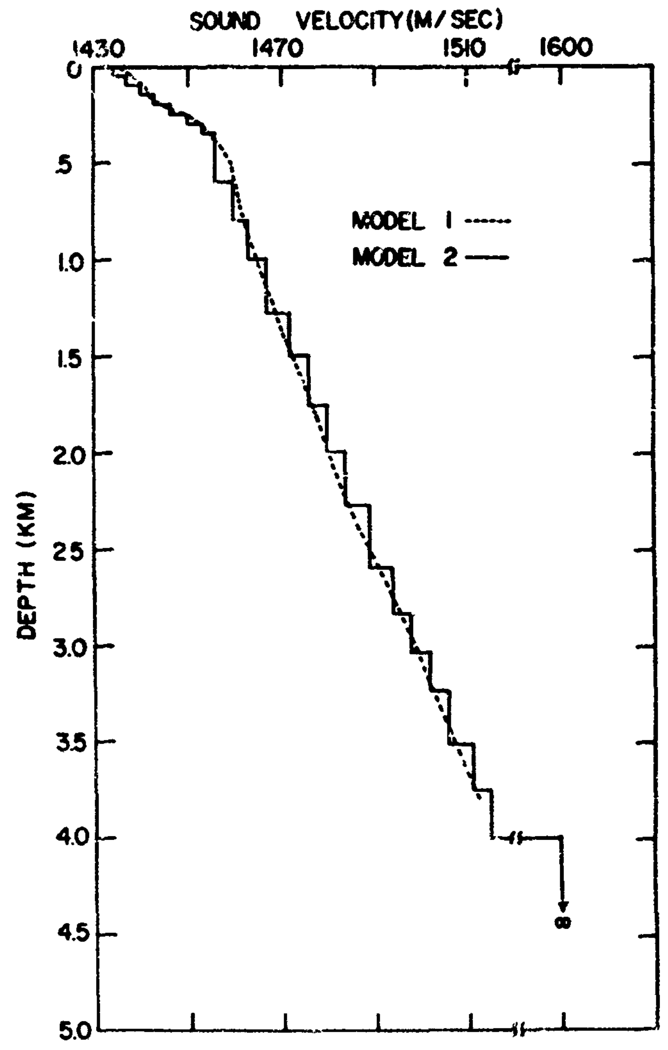

FIG. 1. Models representing the arctic sound-velocity profile.

Propagation

Many aspects of sound propagation in the Arctic Ocean may be understood in terms of ray theory, but at long ranges where low-frequency waves predominate, the solution of the wave equation in terms of normal modes is a powerful method for describing the propagation in detail. Fig. 1 shows sound-velocity profiles which closely follow those observed. Model 1 consists of a sequence of plane parallel layers, each layer having a constant velocity gradient. Such a model is convenient for numerical computations by ray theory. Model 2 represents the continuous variation of velocity with depth by a series of flat-lying layers of constant velocity and density. This representation is extremely useful for solving the wave equation when solid layers as well as liquid layers must be considered. The ice sheet is represented by a layer 3 m. thick, with the appropriate compressional velocity, shear velocity, and density. In the deep ocean the bottom sediments are represented by a liquid half-space, but in shallow water it may be necessary to represent the bottom by a layered solid.

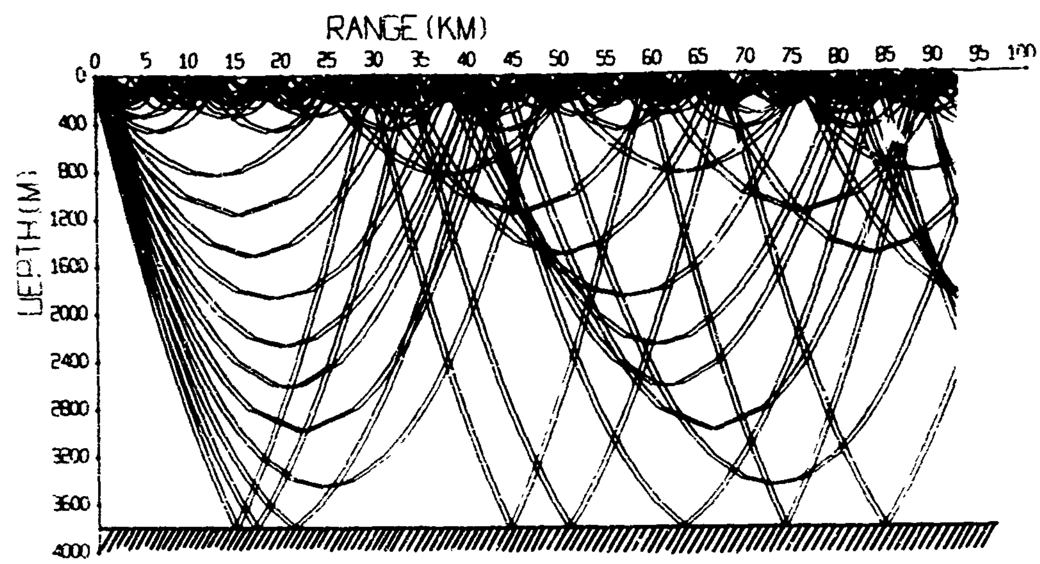

FIG. 2. Ray paths for model 1 of Fig. 1. Source depth 100 m.

Fig. 2 shows ray paths from a source 100 m. deep for Model 1 over the Canada Abyssal Plain in 3,800 m. of water. The concentration of rays near the axis of the channel is apparent. The paths were computed by high-speed digital computer employing a program supplied by the Naval Ordnance Laboratory (Urick 1965). The first refracted and surface-reflected (RSR) sound to arrive at a detector corresponds to the ray which has penetrated to the greatest depth into the channel. The RSR sounds arrive with increasing frequency until they terminate with the arrival of the sound which leaves the source in a horizontal direction. If the detector is deeper than the source, the last RSR sound is the one which arrives from a horizontal direction. The bottom-reflected sounds are generally interspersed between the RSR sounds and they may continue long after the last RSR sound has passed. Except for signals travelling over abyssal plains, the bottom-

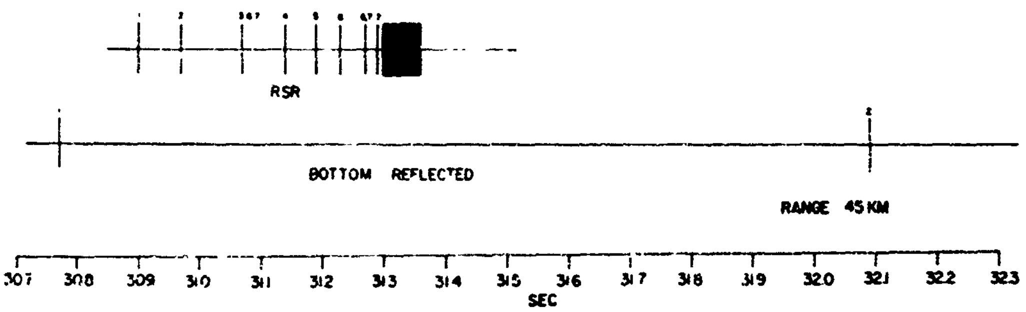

FIG. 3. Time sequence of arrivals for Model 1. Surface source. Surface detector.

reflected sounds have a noncoherent character and they are weak compared with sounds travelling by RSR paths. The first strong sound generally corresponds to the ray which has passed over all bottom topography without striking the bottom.

Any two rays that make the same angle with the axis of the sound channel differ only by a horizontal displacement. The time sequence of sounds travelling by different paths may be determined graphically. An example of the sequence of arrivals is given in Fig. 3 for a surface source and a surface detector separated by a range of 45 km. The number of cycles a ray has made is shown in the figure. There is a duplication or triplication of travel times for rays departing a surface source at angles of between 4 and 10 degrees. At these angles the signal strength is enhanced because of the focusing of sounds by the relatively strong changes in the velocity gradient in the upper 400 m. of water. At long ranges and low frequencies a regular oscillatory wave train is the result of interference of sounds

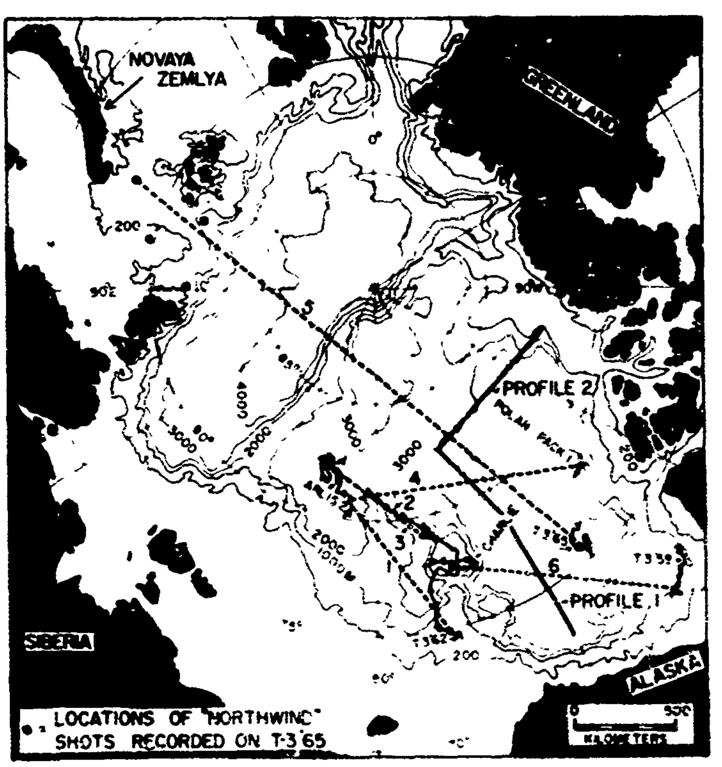

FIG. 4. Bathymetric map of the central Arctic Ocean. Propagation paths are numbered 1 to 6. Transmission profiles 1 and 2 recorded on Fletcher's Ice Island, T-3, during May 1968. Contours based on Geologic Map of the Arctic (1960).

travelling along the various paths in Fig. 2. These are the signals that are conveniently described in detail by normal-mode theory.

Fig. 4 shows the major bathymetric features of the central Arctic Ocean and the locations of drifting stations Fletcher's Ice Island: T-3, ARLIS II, Polar Pack I, and Charlie during experimental periods. Also shown in the figure are shot points occupied by the U.S. Coast Guard icebreaker *Northwind* and Profiles 1 and 2 recorded on T-3 from small TNT charges dropped by a Navy aircraft. Over four hundred shots were recorded and analysed. Ranges extend from 1 km. up to 2,860 km. The bottom topography is variable along paths 1 to 6, but along Profile 1 and part of Profile 2 in the Canada Abyssal Plain the bottom was flat. These transmission runs were made to measure the range dependence of the sound field without any of the effects caused by changes in bottom topography.

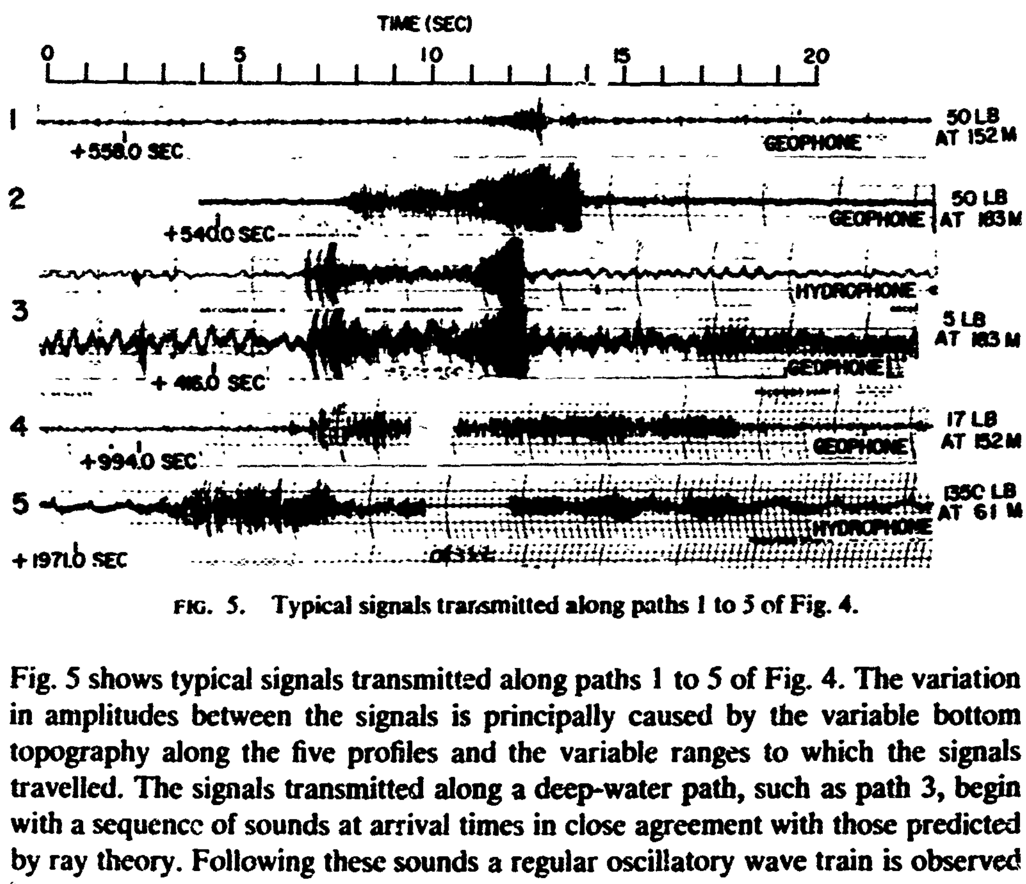

FIG. 5. Typical signals transmitted along paths 1 to 5 of Fig. 4.

Fig. 5 shows typical signals transmitted along paths 1 to 5 of Fig. 4. The variation in amplitudes between the signals is principally caused by the variable bottom topography along the five profiles and the variable ranges to which the signals travelled. The signals transmitted along a deep-water path, such as path 3, begin with a sequence of sounds at arrival times in close agreement with those predicted by ray theory. Following these sounds a regular oscillatory wave train is observed in which frequency increases with time. This wave train terminates with the last RSR sound and is followed by incoherent waves reflected from the ocean floor. The sound spectrogram of Fig. 6 shows that the signals consist of a superposition of many normal modes of oscillation. Waves corresponding to each normal mode exhibit normal dispersion. At ranges greater than 1,000 km. only the first 2 or 3 normal modes are generally observed because of attenuation of waves corresponding to higher modes by the boundaries of the channel. The oscillogram of Fig. 7 shows clearly the regular oscillatory appearance of waves corresponding to the first two normal modes.

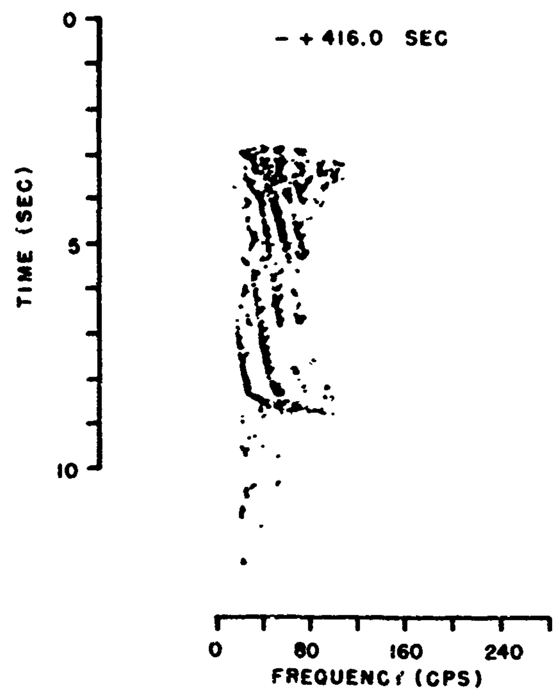

FIG. 6. Sound spectrogram of 5-lb TNT charge fired at a depth of 122 m. Hydrophone at a depth of 46 m. Waves travelled a distance of 609.4 km. along path 3 of Fig. 4.

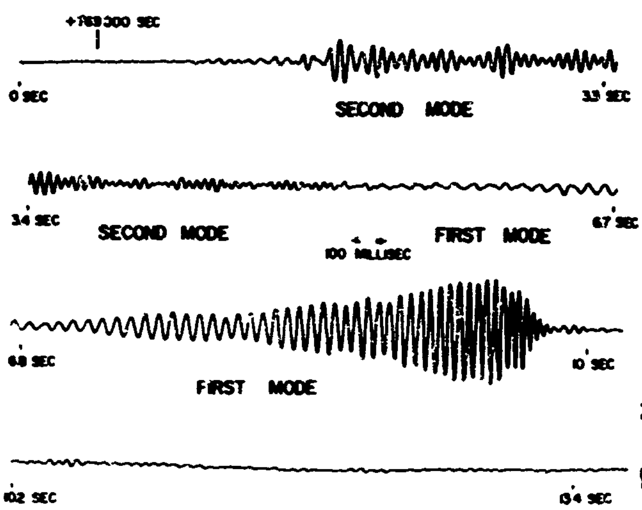

FIG. 7. Oscillogram of signal transmitted along path 6 of Fig. 4. Range 1118.2 km. 9-lb. TNT fired at a depth of 152 m. Hydrophone at a depth of 61 m. Passband of listening system 10 to 21 cps.

The solution of the wave equation for the pressure or particle velocity perturbations generated by point sources in a layered medium makes possible a detailed comparison of observations with normal mode theory. This has been shown in a convincing way by Pekeris (1948) and by Tolstoy (1955, 1958) for acoustic-wave propagation in shallow water. The formulas for an n-layered, interbedded liquid-solid half-space bounded above by a rough layer are very complex and will not be given here. Our analysis, based on the Thomson-Haskell matrix method (Thomson 1950; Haskell 1953), follows Harkrider (1964) for harmonic Rayleigh waves in an n-layered solid half-space. Layer matrices given by Dorman (1962) for computing dispersion in an n-layered liquid-solid half-space are used for the liquid layers, and they are modified at high frequencies to improve numerical precision. The solution for harmonic point sources is extended to explosive sources in the usual way and the Fourier integral for each mode is evaluated by the principle of stationary phase. The model of the underwater explosion at low frequencies and high frequencies for three bubble pulses is given by Weston (1960). Attenuation by the rough ice boundaries is taken into account by multiplying the expression for pressure or particle velocity for each mode by a modified form of the formula of Marsh (1961), Marsh *et al.* (1961), and Mellen and Marsh (1965). The attenuation factor for each mode is an exponential term which is a function of the root-mean-square (rms) ice roughness below sea level, wave frequency, phase velocity dispersion, range for one cycle of a ray as a function of frequency, surface sound velocity, and the distance between source and detector. The additional formulas and subroutines required for the solution of the wave equation in terms of normal modes are incorporated into Dorman's dispersion program for the IBM 7094 or 360 digital computers in either single or double precision arithmetic.

We shall now present some computations for Model 2 and show that the normal mode theory for the layered models predicts quite reliably the frequency and amplitude characteristics of the observed acoustic signatures for Model 2. Fig. 8 shows the range dependence of waves corresponding to the first mode when the surface is bounded by a rough ice layer. Curves of this type show that

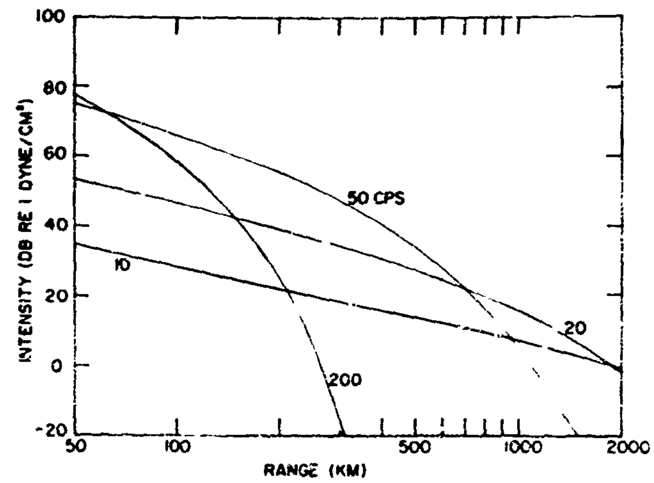

FIG. 8. Range dependence of waves of the first normal mode Computations for Model 2 with 3 m. root-mean-square (rms) ice roughness. 5-lb. TNT charge at 150 m. Hydrophone at 50 m.

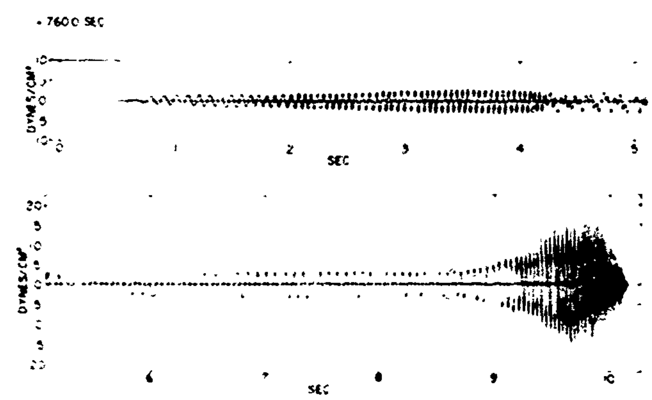

FIG. 9. Computed oscillogram of pressure variations for Model 2. The rms ice roughness 3 m. 5-lb TNT at 150 m. Hydrophone at 50 m. Range 1106.0 km.

low-frequency waves will predominate at long ranges. Fig. 9 shows a computed oscillogram of pressure variations in dynes/cm.^{2} at the hydrophone for the same parameters used for computing the curves of Fig. 8. Waves corresponding to the third and higher modes are neglected since they are weak at a range of 1,106 km. compared with waves corresponding to the first two modes. Although the oscillogram was computed for a charge about half as large as the one corresponding to the signal of Fig. 7, the similarity of the two waveforms is nevertheless striking. Computations just completed specifically for the signal of Fig. 7 are in close agreement with field data. These computations include the response of the listening system and the bathymetry along the propagation path.

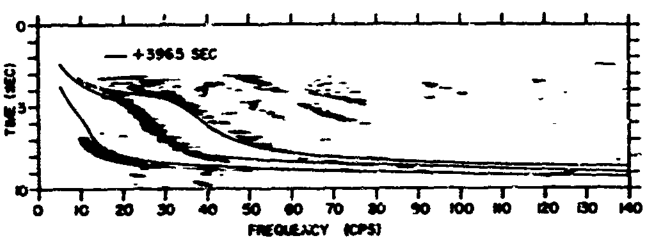

FIG. 10. Comparison of observed and computed dispersion for first three modes. Computations for model similar to Model 2 but with a water depth of 2800 m.

In Fig. 10 an observed sound spectrogram is compared with a computed one for a model similar to Model 2, but for a water depth of 2,800 m. The signal travelled approximately along the deep-water path 3 of Fig. 4. The agreement between theory and experiment is extremely good.

Fig. 11 shows peak signal intensities and peak intensities of waves corresponding to the first normal mode in the band from 25 to 70 cps as a function of range along Profiles 1 and 2 of Fig. 4. The more rapid decay of peak signal intensities along Profile 2 than along Profile 1 is probably due both to a rougher ice surface along Profile 2 and to the bottom topography on the Alpha Cordillera and continental margin. The peak signal intensity corresponds to the deep-penetrating RSR sounds which may have been weakened by reflection from the Cordillera and continental margin. On the other hand, the more rapid decay of waves of the first normal mode along Profile 2 than along Profile 1 is apparently due to the greater ice roughness along Profile 2. Fig. 11 shows computed peak signal

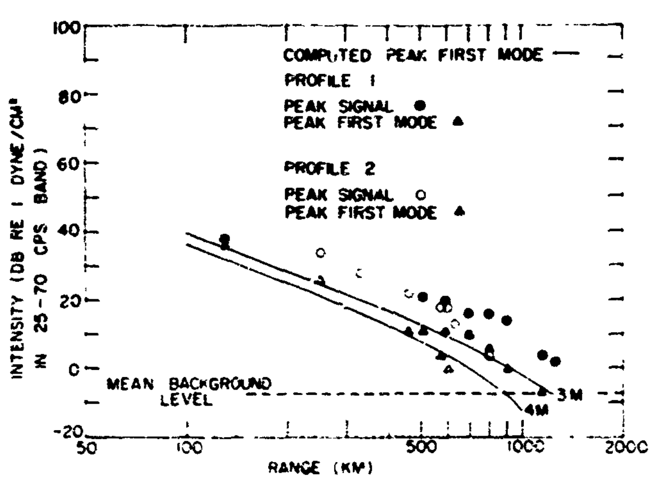

FIG. 11. Peak signal intensities and peak intensities of waves corresponding to the first normal mode as a function of range. Computations for Model 2 with rms ice roughnesses of 3 m. and 4 m. Shots 1.8-lb. TNT at 274 m. Hydrophone at 30 m.

intensities for the first normal mode in the band from 25 to 70 cps for an rms ice roughness of 3 and 4 m. The 3 m. ice roughness fits the data from Profile 1 quite nicely, while at long ranges the 4 m. ice roughness fits the data from Profile 2 reasonably well. The rms ice roughness of 3 to 4 m. is in close agreement with the analysis by Mellen (1966) of Lyon's (1961) under-ice echograms made aboard a nuclear submarine. Our data are also consistent with the transmission loss data of Mellen and Marsh (1965) analysed in terms of energy flux. These workers found that an rms ice roughness of 2.5 m. was indicated by their measurements made largely during the summer and fall months when the pack ice is often broken by large patches of open water.

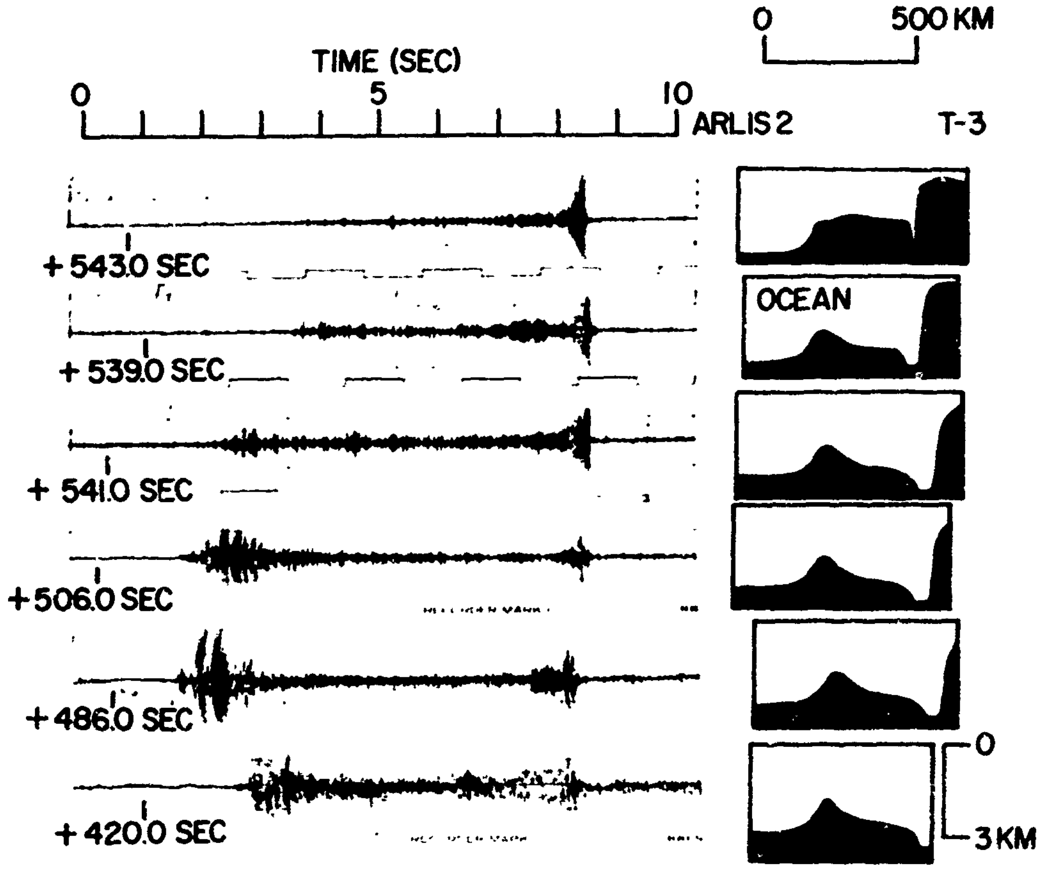

FIG. 12. Oscillograms showing effect of bottom topography on the amplitudes of the waves. Shots 1-lb. TNT at a depth of 71 m. Hydrophone at 46 m. Propagation paths between paths 2 and 3 of Fig. 4.

Fig. 12 shows the effect of bottom topography along the propagation path on the amplitudes of the signals. The sound sources were 1-lb TNT charges fired at a depth of 71 m. The hydrophone was at a depth of 46 m. The propagation paths lay between paths 2 and 3 of Fig. 4. This experiment shows that the first strong sound corresponds to an RSR ray which has passed over all bottom topography without suffering a bottom reflection. For this sequence of shots, the shallowest point along the paths is about 350 m. This corresponds to a speed of sound or phase velocity of 1,454 m. sec.$^{-1}$, and to a group velocity or mean horizontal velocity of 1,445 m. sec.$^{-1}$, which is in good agreement with the measurements.

In shallow water, sounds may be propagated to moderately long ranges by repeated reflections from the surface and bottom. The propagation is not as efficient as in deep water because of the absorption of sound in the sediments and scattering of sound from the ocean bottom. The propagation is generally quite variable depending on the water depth and the nature of the bottom. Water waves from a 1,100-lb TNT charge exploded at a depth of 16 m. were recorded at ARLIS II at a range of 163.5 km. and showed the inverse dispersion of the first normal mode in contrast to the normal dispersion observed in the deep ocean. Fig. 13 shows that this dispersion is in good agreement with that computed for the layered model given in Table 1. Fig. 14 shows diagrammatically the decrease of peak amplitude with range for three shots recorded on ARLIS II.

TABLE 1. Parameters for Computing Shallow Water Dispersion.

Layer	*Longitudinal Velocity* km. sec.$^{-1}$	*Transverse Velocity* km. sec.$^{-1}$	*Density* gm. cm.$^{-3}$	*Layer Thickness* m.
1	1.435	—	1.025	230
2	1.75	—	1.6	200
3	2.7	—	2.08	—

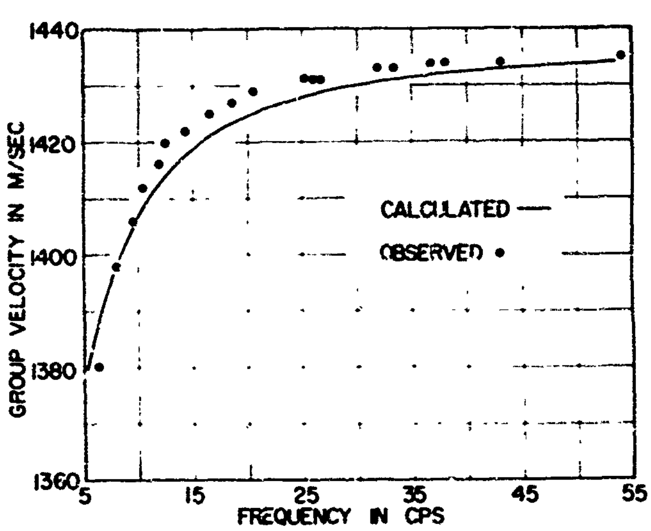

FIG. 13. Observed dispersion of waves of the first mode from several shots compared with first mode computed for model given in Table 1. From Hunkins and Kutschale (1963).

The amplitudes have been normalized to a 800-lb TNT charge. The peak amplitude, which corresponds to a frequency of 18 cps, decreases as the -1.85 power of range in the range interval from 75 to 275 km. rather than the inverse first power of range at this frequency and in this range interval which is observed in deep water. Signals from large charges fired in shallow water have been recorded aboard listening stations in deep water, and also for the reverse situation. In these cases when the length of the shallow-water path is a sizable fraction of the deep-water path, computations are made for each segment of the path separately and they are then combined for the total path.

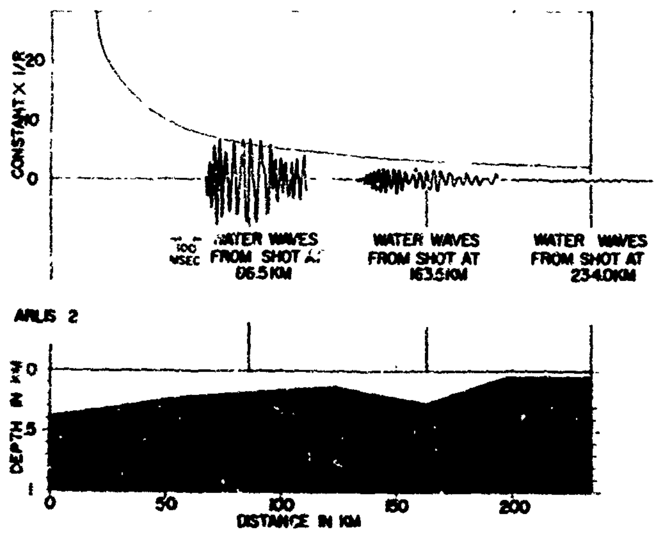

FIG. 14. Water-wave transmission loss and bathymetric profile for shots recorded on ARLIS II. From Hunkins and Kutschale (1963).

Background Noise and Reverberation

An important acoustical parameter of the ocean is the natural background noise. It does not affect sound propagation, but it is extremely important to all aspects of signal detection and processing. An important problem is to isolate the principal sources of noise, measure their strengths, and determine how the noise is propagated away from the sources. Measurements over long periods of time at many locations are necessary to determine dependence of the noise on time, location, and direction.

The principal source of noise in the Arctic Ocean is the ice cover. This ice is in continual motion under the influence of winds and currents and thousands of tons of ice may be displaced vertically and horizontally when a large pressure ridge is formed or a floe breaks up. The air-borne sounds generated by this ice-movement are often heard by ear up to 1 km. from the active area. The sound is commonly a low-frequency rumble. Ice vibrations may also be felt under foot if one is standing on the floe which is breaking up or where a pressure ridge is being formed. Besides these large-scale ice movements, the ice may be under sufficient stress to induce small ice quakes. This is particularly common when the ice is under thermal stress during periods of rapid temperature drop in the spring and fall. The air waves generated by these ice quakes have a snapping sound and their frequency of occurrence may be over one per second. Other sources of noise that may be heard at times are wind-blown snow moving over the ice and gravity waves splashing in open leads.

The natural background noise on the ice and at depth is quite variable in strength. This is to be expected since the noise level depends largely on the relative motion of the pack ice in the immediate area under investigation, and this motion may be from practically zero when all floes are moving with a uniform velocity to highly variable velocities of neighbouring floes during break-up and pressure ridging. The strength of the background noise does not always correlate with the local wind speed, but there is a higher probability of high noise levels during storms than during periods of prolonged calm. The noise may also have a directional character, depending on the locations of the principal ice activity. When local ice activity is low and the noise level is correspondingly low, sounds may arrive from considerable distances travelling in the sound channel. Under these conditions the noise level falls off rapidly with increasing frequency because of attenuation of the high-frequency waves by scattering.

The background noise on the ice and at depth in the ocean is measured by single detectors and vertical and horizontal arrays of detectors. Recordings from a single detector made over long periods of time yield information on the time variation of the noise. Recordings from arrays provide information on the directional properties of the noise and permit an identification of the types of waves present in the noise. Hydrophones at depth pick up sounds travelling along paths like those of Fig. 2. On a typical day, the scraping and grinding of ice may be heard on a loud speaker interrupted occasionally by explosion-like sounds from ice quakes. At night in the spring and fall thermal cracking may be so strong and frequent that noise from other sources above 20 cps is blocked out. The hissing sound of wind-driven snow is heard during storms in the cold months and during the warm months sounds from marine mammals are sometimes heard. On a very quiet day, even the splashing of waves in a nearby lead may be audible.

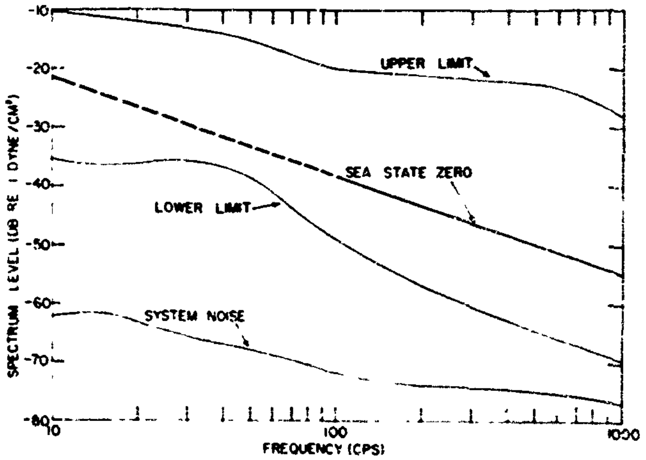

FIG. 15. Upper and lower limits of spectrum levels of water noise. From Mellen and Marsh (1965) and Buck (1968).

Fig. 15 shows the range of spectrum levels measured by Mellen and Marsh (1965) and Buck (1968) with a hydrophone at depths between 30 and 61 m. For comparison, the sea state zero curve of Knudsen *et al.* (1948) extrapolated to 10 cps is also shown. The range of variation of noise levels is more than 25 db, although the average level appears to lie about 6 db above the Knudsen zero sea state curve.

Noise levels in the water generally build up and decay over periods of at least a day, but the ice vibrations may fluctuate by more than 40 db over periods of less than one hour. The waterborne sounds come from many active floes, while the strong ice vibrations are generally confined to the floe on which the seismometer is located. The dominant ice vibrations correspond to flexural waves generated by ice movement at the boundaries of the floe and as this movement increases in magnitude and then weakens so do the flexural waves. The flexural waves are surface waves travelling in the ice sheet and, therefore, pressure perturbations decay exponentially with depth. Only seismometers on the ice and hydrophones directly beneath the ice detect these waves; they are identified by their characteristic inverse dispersion and by the particle motion of the waves. When the movements at the boundaries of the floe are small, then the principal source of noise may be sound transmitted through the water from other active floes, either near or distant. Fig. 16 shows vertical particle motion measured in octave bands from data taken on ARLIS II (Prentiss *et al.* 1966). For comparison, the curves of Brune and Oliver (1959) for land noise and Hunkins (1962) for the Arctic Ocean are shown in the figure. The noise curves of Prentiss *et al.* are for average levels, not for bursts of noise occurring during particularly active times. Even so, the variation of noise levels is more than 30 db, corresponding to levels ranging from very quiet land sites up to noisy land sites.

The total scattering effect from inhomogeneities in the ocean is called reverberation. Reverberation may be subdivided into surface reverberation, volume reverberation, and bottom reverberation. Some aspects of scattering from the surface and bottom were discussed under Propagation; following is a brief description of volume reverberation from the Arctic scattering layer.

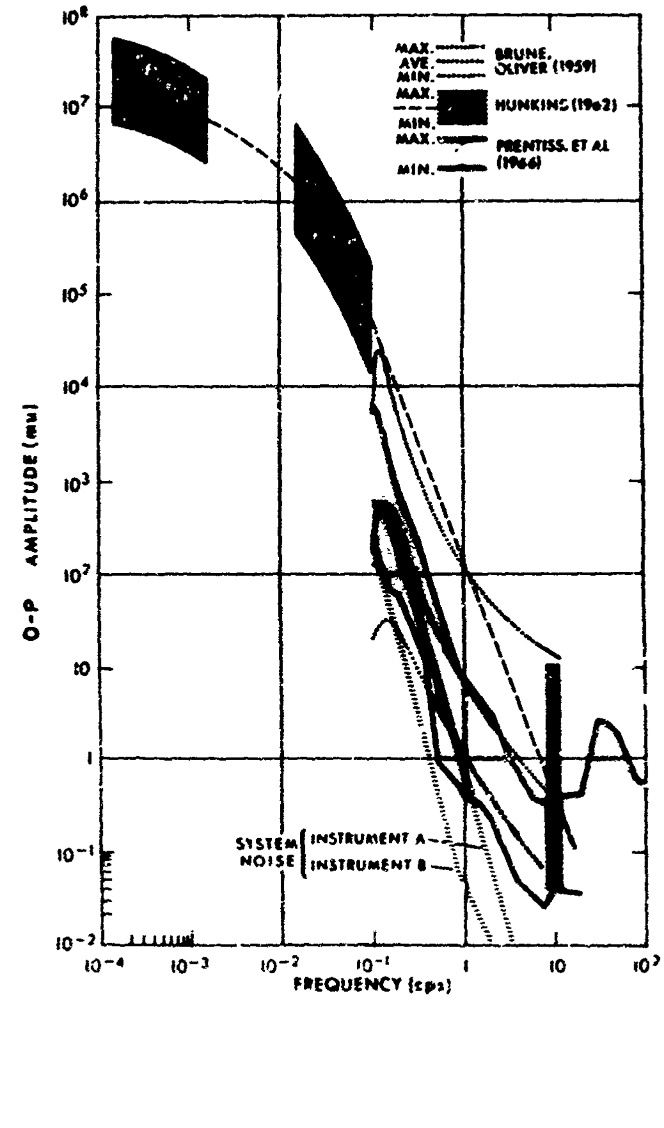

FIG. 16. Ambient ice vibrations recorded on ARLIS II analysed in octave bands. System B was used to record during low noise levels.

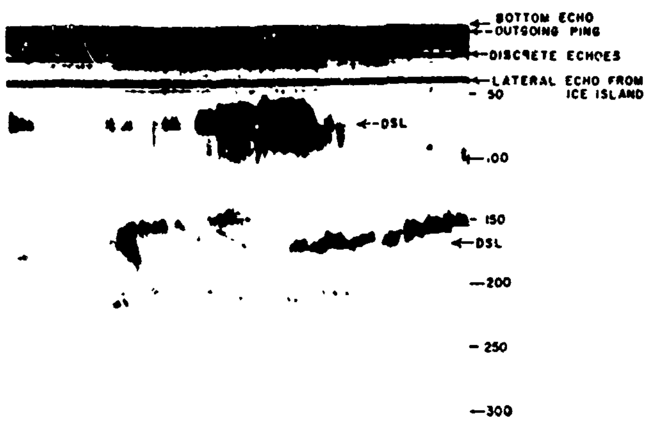

FIG. 17. Precision depth recording of arctic deep scattering layer (DSL). From Hunkins (1966).

The deep scattering layer (DSL) in the central Arctic Ocean was discovered by Hunkins (1965, 1966) in June 1963, aboard Fletcher's Ice Island, T-3. Fig. 17 shows a typical recording of the layer. Precision depth recordings of the layer made up to the present time aboard T-3 at a sound frequency of 12 kc have revealed two important features which distinguish this layer from that observed in the non-polar oceans. The arctic layer occurs at a moderately shallow depth of between 50 and 200 m., and it exhibits an annual rather than a diurnal cycle. This character is apparently a response of the scattering organisms to the unique light conditions present in the Arctic. Light is relatively weak under the ice so that the organisms can find the safety of darkness at moderate depths and the cycle of light and darkness is annual. Consequently the layer is present during the summer and disappears during the winter. At times the arctic scattering layer divides into two or three layers which is similar to what occurs in the other oceans. In addition to the scattering layers, discrete echoes from shallow depths above the layers are commonly observed throughout the year, although they are particularly frequent during the winter months. Presumably, these reflectors correspond to fish or seals. To date, the organisms producing the scattering layers have not been identified but there is some evidence that they may be siphonophores.

FUTURE RESEARCH

Research Platforms

Research in arctic hydroacoustics during the next twenty years will probably continue to be carried out aboard drifting ice stations. Consideration must be given to improving these platforms as listening sites. A major problem of the past has been man-made noise at the stations. This noise comes from heavy equipment used in normal camp operations and from apparatus used by investigators working in other fields of research. Two solutions of this noise problem are possible. One is to move the listening site far enough from the areas of activity so that the noise is negligible. The other is to establish a drifting station which is designed especially for quiet operation. In both cases maintenance of a camp is required. The latter possibility is particularly attractive for future work, since a station in addition to Fletcher's Ice Island, T-3 is required for detailed experiments on sound transmission. The new station should preferably be on pack ice to provide acoustic data under typical ice conditions in the central Arctic Ocean. A suitable initial location for the station would be near the centre of the Canada Abyssal Plain. This station would remain over the Plain for a reasonable period of time whereas T-3 might pass over other bathymetric features. Every effort should be made aboard the new station to minimize man-made noise. Generators should be quiet, but provide reliable power for the equipment. The camp should be small and mobile so that in the event of breakup it could be moved to another suitable floe in the area. In addition to serving as a listening platform for long-range transmission work, the new station would be particularly suited for investigations of ambient noise, reverberation from the underside of the pack ice, short-range transmission in the ice and water, and as a test platform for new hydroacoustic apparatus. For sound transmission experiments, explosives could be launched from both stations, but high-power harmonic sound sources should be installed aboard T-3 or the successor to this ice island to avoid noise at the quiet station. Satellite navigation would provide precise positions of both stations. Listening could continue aboard T-3 at sites sufficiently far removed from the main areas of man-made noise.

Oceanography

Of basic importance to the interpretation of hydroacoustic experiments are the physical properties of the medium in which the waves travel. Hydrographic stations provide the data to determine in detail the seasonal and regional variations of sound velocity with depth. Although a considerable body of data has been obtained in the past from drifting stations, more area can be covered by aircraft landings on the ice. A worthwhile project for the future is to measure sound velocity profiles at many locations with a portable velocimeter carried to the station by aircraft. Ocean currents and internal waves in the upper layers may have important effects on sound intensities at high frequencies. Continuous measurements of currents and temperatures at depth should be made simultaneously with a transmission experiment between a fixed transducer and hydrophone separated by perhaps a kilometre or two. Drifting stations provide a unique opportunity for such a detailed experiment.

More data on bottom and under-ice topography are required for investigating effects of variations in this topography on sound transmission. Ice roughness varies both seasonally and regionally and therefore significant differences in signal strength at different seasons and locations are expected. For computations of bottom-reflected sounds by ray or mode theory, the bottom topography along the transmission path must be known. Only in a few cases are there sufficient data to model the bottom topography even approximately. Although ice stations will continue to supply high-quality precision depth recordings, only measurements from nuclear submarines can provide the regional coverage required and data on both the upper and lower boundaries of the ocean. Under-ice echograms obtained from submarines should be analysed in detail to determine the roughness spectra of the underside of the ice as a function of location and season. These data might be supplemented with transmission profiles made along the submarine track either by launching small charges from the submarine or from an aircraft.

The elastic constants of sea ice are established from seismic experiments (Hunkins 1960), but our knowledge of the elastic properties of the bottom sediments in the central Arctic Ocean is meagre. Most of the information we have comes from sound velocity and density measurements made on bottom cores. This work should be supplemented with wide-angle reflection and refraction profiles made periodically aboard a drifting station to measure the velocity distribution in the sediments.

At phase velocities greater than the speed of sound in water, sounds travel in the ice by repeated reflections from the upper and lower boundaries of the ice. High-frequency waves are attenuated strongly not only by scattering from the boundaries, but also by inhomogeneities in the sea ice. Laboratory experiments on attenuation in ice have been made and these data should be supplemented by measurements in the field at various frequencies and at different times of the year.

Propagation

Experiments on long-range explosive sound transmission should be designed to investigate the effects of variations of ice roughness and bottom topography on signal strength. These experiments can be efficiently carried out with aircraft dropping charges into open leads. The location of the listening station is important and it should be over an abyssal plain so that some profiles are over a flat bottom and others show the effects of bottom topography at one end of the profile only. Propagation experiments made on a year-round basis between two drifting stations might reveal significant variations of signal strength which could be explained in terms of ice conditions, bathymetry, and small variations in the velocity structure in the upper layers of the ocean. More data should also be obtained between two drifting stations for the variation of pressure level with source or detector depth. These measurements are best made by keeping the shot depth constant and varying the hydrophone depth to at least 800 m.

Computations by normal-mode and ray theory should be compared with measurements of sound fields from harmonic sound sources at frequencies from 10 cps upward. Measurements at various frequencies and detector depths made between two drifting stations positioned by satellite navigation would provide detailed data on the variation of pressure with depth and frequency and on attenuation of waves by the ice boundaries as a function of frequency. The measurements could be repeated periodically to obtain the range dependence of the sound field at the operating frequencies. These data might be supplemented by a transmission run by submarine. This type of profile has the great advantage of a continuous record of sound pressure level as a function of range, together with the important data on the shape of the surface and bottom.

Background Noise

Long-term measurements of background noise are being carried out aboard Fletcher's Ice Island, T-3 (Buck 1968). Measurements of this type should also be made aboard a quiet pack ice station under typical ice conditions. The noise levels must be carefully examined in terms of environmental conditions, such as local winds, ice movement, and air and ice temperatures. Measurements employing horizontal arrays of hydrophones and seismometers provide data on the directional properties of the noise. The interpretation of these data is greatly assisted by air photographs made periodically over the area under investigation to determine the active areas of ice movement. A promising new tool for investigating the regional variation of noise is the IRLS system. This remote sensing platform transmits data via satellite to a distant manned station. An experiment in the spring of 1969 aboard T-3 was designed to establish the possibility of using this platform to gather noise data at unattended sites in the Arctic Ocean.

A problem of basic importance to computing theoretical noise spectra in terms of propagation models is to know the spectral characteristics of the noise sources. Portable listening equipment installed at active pressure ridges and leads would provide such data for the large-scale ice movements. Milne (1966) has computed the spectral characteristics of thermal cracking for a model of the sources and he has obtained reasonably good agreement with measurements made under shore-fast ice. Thermal cracking of sea ice investigated in the laboratory under controlled conditions might provide useful data to determine the critical temperature gradient required for the onset of cracking and the peak amplitude distribution of the ice tremors.

Reverberation

A hydrophone near an underwater explosion detects strong reverberations from the underside of the ice. It is expected that these reverberations are strongly dependent on local under-ice topography. This appears to be the case for the data of Mellen and Marsh (1963), Milne (1964), and Brown (1964). The data of Milne and Brown, although not in agreement, show an increase of scattering strength with frequency and grazing angle, while the data of Mellen and Marsh indicate an absence of frequency dependence. Marsh and Mellen have derived the ice roughness spectrum from their data, but this spectrum is in poor agreement with the spectrum computed by Mellen (1966) from Lyon's under-ice echograms. More measurements should be made at various locations and seasons of the year for comparison with predictions made by theory for models of the under-ice topography.

Drifting stations provide ideal platforms for experiments on volume reverberation. The seasonal and regional characteristics of the DSL may be measured along the drift path from recordings made over periods of years. Biologists can probe the layers for samples of the scattering organisms. Present sounders aboard T-3 operate at 12 kc. and 100 kc. These measurements should be continued and extended to other frequencies. Reverberation levels as a function of depth at a number of frequencies should be measured periodically aboard the stations.

Strong bottom-reflected sounds are commonly observed over abyssal plains at ranges up to 500 km. from an explosion. In almost all cases over rough topography, bottom reverberation is observed at long ranges beginning with the onset of the RSR sounds and continuing many seconds after the last RSR sound has passed. The sound spectrogram of Fig. 6 shows this reverberation clearly. Future experiments should measure the level and spectral character of this reverberation as a function of range, bathymetry, charge size, and charge depth. The data at long ranges should be supplemented with bottom reverberation measured at the ice stations from local explosions as the stations move over different bottom topography. Precision depth recordings and ocean-bottom cores will aid in the interpretation of the reverberation data.

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Marine Biology

J. L. MOHR[1]

CONTINENTAL SHELF

Introduction

Research in marine biology carried out from the Naval Arctic Research Laboratory or through it and interlocking agencies provides a substantial base for more refined studies requiring arctic or subarctic marine organisms or conditions. Before 1948 (see MacGinitie 1955, pp. 1-3) observations were so few as to be almost useless. In the course of work in 1948 and 1949, MacGinitie and co-workers studied mainly the benthic invertebrate fauna of the continental shelf area and Elson Lagoon close to the laboratory (about 71°20′ N., 156°41′ W.). To one familiar with the environment and the equipment they had, the MacGinitie team's results approach the awesome; they could be accomplished only by a combination of unusual knowledge of the ways of invertebrates with practical seamanship and almost unbelievable persistence. Use of the superlatives these scientists deserve would probably alienate anyone not acquainted with the difficulties under which they worked. The extent of their contributions may be indicated by the fact that earlier workers had reported the presence of a few amphipods and a few polychaetes; the MacGinitie team studies (MacGinitie 1955; Pettibone 1954; Shoemaker 1955) cover about 100 species of amphipods and 88 polychaetes with considerable information on behaviour (particularly of breeding) and ecology. Because of the smallness of the team, the brevity (less than two years) of the field work, and the paucity of equipment, the scope was also very limited.

Inventory

Most of the work from Barrow in marine biology to date has been devoted to inventory taking. Because the chance for a role of distinction for NARL in marine biology depends precisely on the attraction of superior experimental biologists and these will come to the laboratory only if dependable supplies of experimentally intriguing organisms are provided, a good inventory with easily retrievable data is indispensable.

The MacGinitie studies provide the core block of knowledge mainly of bottom invertebrates within a few miles of Barrow. Subsequent work near Barrow increased the knowledge of the fishes and cetaceans (Maher and Wilimovsky 1963; Hurley and Mohr 1957) and some parasites of marine vertebrates (Rausch 1962; Schiller 1967). Another study (Mohr *et al.* 1957) revealed a bed of marine algae (the Skull Cliff "kelp bed") about 50 miles west of Barrow, and confirmed an

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existing impression that the biota is rather poorer east of Point Barrow and a little richer westward toward Wainwright.

Besides being limited mainly to the inner portion of the arctic shelf, which averages about thirty miles wide, the knowledge is mainly about animals that, with the exception of the foraminiferans, are large and conspicuous. Anything which might slip through a millimetre mesh was ordinarily not taken or was lost in the washing of bottom deposit material.

Observations are also limited mainly to periods of open water; MacGinitie did under-ice dredging (devices other than dredges have very small yields) accomplishing by dint of great effort *two* hauls in February and *one* in March during his 1949-1950 work. I find no report of other winter dredging. Thus there is little good winter information, and as there has been so little shelf work done since 1950 there are no data on how the stock changes through seasons and years. (Compare this with the information amassed on the lemming.) Neither is there information on how many individuals of any species occur off Barrow, except for the very general knowledge that more of some things than of others were taken.

For a brief period in one year Wilimovsky (1954) and his associates used a beam trawl with aperture eight feet wide from the LCM *William E. Ripley* and some years later another researcher had just a few hauls with a six-foot aperture Isaacs-Kidd midwater trawl. Neither was used often or widely but their rake indicated clearly that the swifter and shyer species and the adult stages of some species were not represented in proportion to their actual occurrence in nature in the earlier collections.

Another deficiency of the existing inventory is the uncertain location of the stations. The best locations are only fair; those farther to sea, vague.

Plankton of the inshore area, in which some interaction with shore and bottom should occur, has barely been examined. Johnson's (1953) studies, which have the only grid of plankton stations, barely touch the inshore area. Bursa (1963) had very limited collections of the phytoplankton. Virtually all the sampling has been done in summer. There has been no sampling in the leads in April and May when the bowhead whales are hunted while apparently feeding; I have guessed that the zooplankton is heavy then and that its growth has followed an earlier and significant increase in phytoplankton. F. E. Durham (personal communication) has some bowhead gut material indicating that they do feed (most whales apparently disgorge when they are harpooned), but almost nothing is known of the plankton which is their food.

Systematics

Taxonomy of Barrow organisms has taken little account of variability or population phenomena (except for Holmquist's (1965) studies), karyotypes, chemical characteristics, or other aspects of current major taxonomic concern. Some macroscopic groups (for example sea squirts) are still to be given first comprehensive study. Specialist studies, such as that of Steele and Brunel (1968) on the amphipod, *Anonyx*, will describe more clearly a larger macrozoan fauna than we now know.

Greatest changes will come in our knowledge of small forms. Even "alpha" taxonomy has yet to be done with unicellular algae, the bacteria, the protozoans other than foraminiferans, and the spirochaetes and more obscure microbes of the sea. On grounds of biological logic, that is, in the sense that in microbes most energy transformations take place, they must be of vast importance. Presumably cryophylic, they should at least rival in interest counterparts on the land.

In addition to the protophytans and protozoans, essentially untouched groups of small forms include hydroids, turbellarians, nematodes, rotifers, Kinorhynchs, and the "micros" among the mollusks, segmented worms and arthropods; in sum probably considerably more organisms than we know at present.

A principal service needed *from* the taxonomists is the preparation of a series of aids that will permit a properly attentive worker, for example a systematist with no knowledge of a particular group, or a physiologist with no experience whatever with naming organisms, to know any organisms occurring often enough and in numbers enough to be suitable for experimental studies.

Aids should include carefully constructed keys, with good diagrams, photographs, measurements, and a modicum of ecological detail. As MacGinitie originally provided with the amphipods, the systematists should supply the laboratory with a working colour-print atlas of living examples of several important groups. Especially appropriate for inclusion would be the amphipods in which living examples at dissecting scope magnification characteristically have distinctive colours, although in preservative for even a short time they tend to fade to disheartening homogeneity — as a nonspecialist sees them. These animals are potentially of real importance for experimental purposes, but the potential is not obvious as one examines, for example, the accounts of 100 species of amphipods covered in Shoemaker's (1955) paper, illustrated mainly with dozens of pedal and antennal details of leached-out remnants. In life many have distinct colouration and they have behavioural, physiological, and other problems more than enough to keep a laboratory full of good biologists busy with worthy problems.

Microscopy

Few investigators have sought small free-living organisms or have examined any of the marine organisms microscopically. To observe the effects of the parasite, Thalassomyces, I studied sections of one infected individual of the pelagic amphipod, Parathemisto. It proved to have gregarine protozoans in the midgut and ciliates, probably suctorians, on swimmerets; the Thalassomyces had pushed aside the central nerve cord. In about a year of study of calanoid copepods of the basin and the northeastern or eastern Greenland waters, Julio Vidal (personal communication) isolated calanoids of at least five genera (Augaptilus, Chiridiella, Microcalanus, Scaphocalanus, and Spinocalanus) with suctorians attached, well over a hundred individuals. From these and other observations one may remark that energetic investigation with the naked eye, but especially with dissecting and compound microscopes, will discover very many parasitic (broad sense) relationships; furthermore that an almost infinite spread of significant problems of structure and function is to be found at the microscopic level in organisms from the dinoflagellates to kelps and ciliates to cetaceans; and that even a modest beginning has yet to be made.

Biogeography

The Barrow area has yet to be placed in a marine biogeographical context by anyone familiar with its organisms. It appears in various accounts usually with Barrow matters somewhat out of focus. The significant adjacent areas also are very poorly known so that a biogeographical synthesis cannot now be adequate. Generalizations which lump the Barrow area with the Grand Bank off Newfoundland as "subarctic" are misleading.

Ecology and Animal Behaviour

The materials for consequential ecological studies of the Barrow marine biota are not yet at hand. The MacGinitie work was illumined by a master ecologist's understanding and the summary study (MacGinitie 1955) is a masterful guide and a beginning to an ecological study of the region. The fact remains that an inventory and an ecological analysis of the results cannot be made anywhere by a handful of people with minimal equipment in eighteen months — and Barrow presents more difficulties of operation than most other places.

There is no comprehensive web of geological stations although a few observations at sea have been made in the course of beach or permafrost studies. As most inshore areas, Barrow lacks proper oceanographic studies. Determinations of turbidity, temperature, salinity and dissolved oxygen have been made mostly by people without special competence for the work. Also lacking are measurements of such important factors as light over and under water and ice, and of major and minor nutrients. The measurements that have been made have little spread in space or time. There are too few covering too short a time.

MacGinitie (1955) and others (Mohr and Tibbs 1963; English 1961) have tended to emphasize the importance of limitations on light: angle of entry into water, turbidity, ice and snow reflections, and others; Dunbar (1968) appears to de-emphasize such limitations emphasizing rather the extraordinary efficiency of polar marine unicellular algae, high in chlorophyll C, in using light of low intensity. Whatever is the emphasis, there is yet to be amassed a proper body of measurements of the energy received by the biological web at Barrow; of the light penetrating the sea and some calculation of how much of it may be used by what organisms (neither planktonic nor benthic plants are properly known); of the energy available from tundra sloughing or from materials carried from the land by rivers, or into the polar enclosure by ocean currents.

The MacGinitie summary paper either starts or indicates community studies that need to be made, but so far there is at most inadequate information even of what (particularly how many of what) occurs where. There is need for sampling devices that do not dislodge organisms from their positions on or in a bottom sample. Devices such as anchor dredges or the modified Campbell grab with camera may be partial answers to sampling difficulties. There is little knowledge of the interaction of organisms with physical environment, with others of the same species, or with other kinds of organisms. There is no knowledge of population changes or interactions.

Ecological studies such as plot or transect analyses, which may be carried out by wading or diving with only moderate difficulty in other areas, are grossly hampered at Barrow by the ice cover and by sediments made into slurry by grinding ice and currents. There is virtually no possibility of useful intertidal studies. Subsurface studies going beyond a single season would need to be in deep enough water not to be demolished by pressure ridges in the ice cover. Such work would impose great difficulties of relocating and sampling. Several programs that offer considerable prospects of significant results are suggested.

The first of these is to set out extensive artificial reefs deep enough (approaching 50 feet, for example) not to be dislodged every winter by pressure ridges. These would involve depositing discarded metallic objects as a linear reef normal to the shore-line, possibly with satellite cluster reefs. With metal lines and buoys attached at the start, they might be provided with removable panels for study of interactions of organisms, fouling, succession, and the like, with panel information supplemented by trap results. The ferric mass of many drums and fractured vehicles should be readily relocated and divers might reattach lines and buoys. Wherever artificial reefs have been constructed so far, they have been taken over promptly by the organisms of the area and have ranked with the sections of high population in the surrounding areas.

A second approach is that of the marine pond. For this our models are Mogil or "Grave" Lake of Kildin Island on the Murman coast, and Nuwuk Lake at the tip of the Point Barrow spit. In both cases there is a lake deep enough to have an unfrozen pool large enough to counteract evaporative water loss (in Grave Lake, according to report percolation from the nearby sea maintains a normal arctic seawater salinity), and with a drainage basin broad enough so that the closest tundra sloughing does not make the lake dystrophic. Such a lake is a limited marine microcosm which can be modified systematically in a series of experiments. Because Nuwuk Lake is now on an island (it was readily accessible between 1952 and 1960 when previous observations were made), it would probably be necessary to install a wannigen station for observers or to excavate and build up one or more similar basins closer to the laboratory.

There are many potentially fruitful experiments with such a marine pond that suggest themselves to any ecologist. After measurement of dissolved elements one might augment one or more of the trace elements that are at particularly low levels and effect other types of fertilization indicated by levels of nitrogen compounds. After a check of conditions and populations in one year, one might stir the bottom sediment (that of Nuwuk Lake is a deep deposit of sulfide mud) a little or much with pumped air or with oxygen, after which all should be studied again. One might introduce various primary producers — an inoculum of a unicell such as an arctic diatom or one of the smaller species of brown or red algae from the Skull Cliff kelp bed. One might introduce living barnacles or some other fecund consumer and one might, with particular profit, set up an artificial reef. "Management" of environmental factors and accuracy of measurement are obviously possible beyond anything practicable in the open sea, whereas such a system escapes many of the disadvantages of a laboratory tank. Experience with the unmanaged events in Nuwuk Lake gives confidence that good experimental designs could give worthwhile scientific yield.

Tank or flask studies in the laboratory may produce other useful results as they do at other latitudes. They are very likely to be particularly valuable with unicellular algae and protozoans for which responses to light (in the many ways it is known to affect organisms), temperature, agitation, nutrients, associated organisms, accumulated metabolites, and so on, are probably significant. One might test d'Ancona-Volterra (= Gausean) competitions, Margalefean succession, and other ecological models.

In summary, ecological marine research has barely begun at Barrow; it is very likely to be attended by exasperating difficulties, but there are possibilities of results of the same high interest as those developed in arctic terrestrial ecology.

One utilitarian ecological task that is seriously overdue is a study of pollution of the northern sea. In an earlier day Eskimo villages did not grow beyond the capacity of the nearby land and sea to yield enough fish, game, and whales to provide protein. Eskimos in such villages produced little that did not disintegrate inoffensively in a few seasons. Barrow today has both much greater amounts of waste and many new persistent objects and substances. On shore in summer it is visually and olfactorily degraded; at sea there have been *no* observations. With bacterial decomposition slowed by cold, one must guess that bottom organisms are affected adversely, but it is necessary to examine the area to find the extent of any sludge and the degree to which a health hazard may exist. The area of contamination also restricts the possibility of any exploitations of shellfish.

The exploitation of northern oil, so far as it touches on the sea, presents quite another set of problems, for the equipment used and the intensity of the operation make for very rapid changes. From Californian experience, it is feared that the operator will show little foresight in pollution matters and little concern for the environment. The lack of concerned observers augurs ill for ecology. In their studies of 1949 and 1950 George and Nettie MacGinitie (as would be anticipated from their many contributions to knowledge of behaviour of Californian invertebrates) made many observations on behaviour of Barrow organisms (relations of commensals to various hosts, colonial behaviour of certain amphipods, and so on), but these were mostly aborted at the level of asking a significant question, because time was inadequate, and decisively, because temperature controls failed continually and animals died.

Many significant problems in marine animal behaviour may be studied at NARL with rather modest modifications of or additions to existing equipment (circulating seawater, light and temperature controls). Obviously appropriate programs are those involving responses to conditions of high as compared to lower latitudes, and particularly those related to extremes of available light and food. Possibly most fruitful would be studies of individuals of the same species (as certain crustaceans, annelids or mollusks) from Barrow and from Friday Harbor, or Churchill. Undertaking joint studies with laboratories with established germane programs is desirable.

Generalizations about the effects of latitude on the size of marine plants and animals are among those that should be tested. For example, with barnacles one might determine normal sizes with age, rates of shell growth, maximal ages and survivorship, attainable sizes, and the like. The notion that polar animals are larger, certainly not true for larger taxa, may be true for a species extending through many degrees of latitude.

The use of Nuwuk Lake or of artificial marine ponds would increase the range of experimental possibilities for animal behavioural studies.

Embryology and Life Cycles

Investigation of the development of marine organisms might not seem an especially appropriate activity for what is, indeed, an outpost-laboratory. There are, however, very good reasons for regarding embryology as having a potential role of especial importance for NARL. MacGinitie (1955, esp. pp. 36-53) has provided data on "reproduction phenomena" on nearly 150 species of eleven phyla of invertebrates. Although few of these have been maintained in the laboratory, Mohr *et al.* (1961) found in Nuwuk Lake apparently flourishing foraminiferans and several other sorts of protozoans, flatworms, roundworms, a nemertean, a priapuloid, a bivalve and a gastropod mollusk, a small earthworm, several polychaete worms, and crustaceans (one species each of ostracod and mysid, two amphipods, and more than a dozen copepods). Because Nuwuk Lake is, or was, a rather poorly nourished lake with an ice and salt regime and a vulnerable food web, those of us who have worked there believe that a number of the inhabitants may be sufficiently hardy to be good laboratory animals. The development of the whole curious group, priapuloids (a species of which at least occurred in Nuwuk Lake) is very incompletely known. Some other Nuwuk animals and quite a few of the species (coelenterates, mollusks, polychaetes and tunicates) that MacGinitie found breeding are fairly closely related to species used in classical and experimental embryological studies. The echinoderms, although not observed in breeding, are worth investigation.

How much one might do with studies of living marine algae must be determined. The kelp bed off Skull Cliff would very likely yield the same algae that were taken when it was discovered: three browns and seven reds. Provided that they were not dislodged from the rocks they were growing on and that they were given nutrients and trace metals, these should thrive in the real or a synthetic Nuwuk Lake and some should be suitable for laboratory propagation. Alternation of generations, fertilization, morphogenesis, growth rates and the like could be studied.

I believe that no cycle of a marine organism has been worked out at Barrow although the cycles of a few species that occur there have been studied at laboratories at lower latitudes. In the cases where a cycle is known for a species in an area with quite a different environment, it is possibly desirable to determine how development has responded to the special conditions of a far northern habitat. Knowledge of the life cycles of principal marine organisms: when and where they breed, how many eggs of what kind are carried or placed where, what stages develop how rapidly, when and where they mature, and so on, is indispensable for work on population ecology. It is a prerequisite also for many kinds of experimental studies, particularly physiological studies.

J. F. Tibbs (in discussion and in letters) has pointed out that polar seas, both north and south, at latitudes above those with subarctic or subantarctic abundance should be particularly favourable for working out life cycles. Because there are no more than a few species in most families, organisms are likely to have developmental stages that need not be confused with those of closely related organisms. Where there are two or several species with developmental forms similar enough to be confused, breeding of the different species, characteristically not prolonged in cold waters, may not occur at the same time.

Tibbs hopes to follow the development of radiolarians, an important marine group on which earlier work on developmental cycles is known to be mistaken. Because radiolarians have not responded well to culture, complete cycles have not been determined in any laboratory. It appears that it should be a relatively uncomplicated task working from Barrow or a drifting station to fit developmental stages into a correct sequence provided that frequent plankton samples were taken with fine nets sufficiently gently so as not to shatter the fragile radiolarians.

Probably even more important would be to determine the reproductive events of a number of radiolarians where existing accounts are either known to be mistaken or are at least suspect.

Physiology and Biochemistry of Marine Forms

Other papers presented at the NARL Symposium have stressed studies of temperature relationships; much remains to be done with marine organisms.

One might find in at least ten chapters of Nicols' (1967) book on marine animals problems in which studies of Barrow animals would significantly expand knowledge. Species that are apparently common, and whose size and other characteristics are suitable, could be suggested for many studies. Recently a chemical neurophysiologist, seeing specimens of the large isopod, Mesidotea (Idotaega), remarked that it should be ideal for both electrical and chemical studies of vision.

The range of organisms for marine plant physiology, while smaller, is enough to support significant research. Northern phytoplankton has been subjected to few experimental studies. NARL should be an excellent base for getting cold water forms into culture and for studying a variety of environmental and nutritional effects (as well as providing food for experimental animals). The few macroscopic marine algae that one may be confident of collecting are enough for many studies of environmental effects. I believe there have been no studies of photosynthesis, energy transfer, respiration or other physiological processes in far northern marine plants. *Ulva* (fragments of which have been taken), and three brown and seven red algae provide a range of pigments and most likely a range of physiological modes. Measurements of their physiological parameters should have the same high levels of interest and importance that the pioneering studies of Irving (1951), Scholander *et al.* (1950), and Wohlschlag (1953) have had.

The biochemical study of Barrow marine organisms is to my knowledge confined to the single study of Lewis (1962) on chain length and unsaturation of lipids of a fish and a crustacean. His approach (gas chromatographic analysis of methylated lipids) should be extended to an analysis of annual cycles of kinds and amounts of lipids in the same and in other prominent species, and should be combined with studies on the morphological disposition of the lipid pool and of its physiological role.

Of all the physiological-biochemical studies, I should name the isolation, chemical identification and functional characterization of principal enzyme systems as having the greatest interest for polar biologists. In these cryergic enzymes, rather than in any visible structure or process, is the difference between Barrow organisms and those of lower latitudes. Their elucidation should be a task of high priority.

Other biochemical objectives of many sorts are well worth pursuing: carotenoid pigments of crustaceans, especially euphausiaceans; photosynthetic and associated pigments of unicellular and of macroscopic algae; visual pigments of many animals; dermal or epidermal pigments of crustaceans, cephalopods and fishes; serological systems of fishes and mammals; differences in biochemistry of bowhead whales, and belugas (which do not leave northern waters) and gray whales (which migrate to tropical Mexico each winter), and so on.

At this stage in the life of NARL, the most appropriate biochemical problems for study are those that can be started with sampling at Barrow and carried to a stage at which further changes can be restrained until materials are taken to a complete biochemical laboratory. In the future the biochemical capabilities of the laboratory may well be increased.

To a very important extent the history of genetics has been the finding and exploiting of a series of organisms in which it has been possible to associate an underlying hereditary mechanism and a clearly defined expression of that mechanism (a structure, a behavioural pattern, a chemical compound) in which generations are short, and which are easily bred. So far few marine organisms have been proposed for genetic studies (Ray 1958), but this is probably so because few marine organisms have been "domesticated". There is no reason to suppose that few marine organisms suitable for genetic studies exist or that they are absent from polar seas. Properties such as those related to life in the cold obviously have potential interest for geneticists. Unicells (bacteria, algae, protozoans) seem particularly likely candidates for roles in genetic research. However, geneticists, with notable exceptions, esteem comfort and convenience; they would probably require services and support not now contemplated.

Marine Fishes and Mammals

Barrow area fishes were studied for some years in the early fifties by Wilimovsky and his several co-workers. Like the MacGinitie work, theirs was largely inventory with similar uncertainties about places and numbers, and some information on breeding states was obtained. The range of collecting was somewhat wider: Barter Island to Kuk Inlet; and some more adequate equipment (*e.g.*, a large beam trawl) was used in the Point Barrow-Kuk Inlet sector. Much of what has been said above about systematics, ecology, behaviour, and so on, of invertebrates can be applied to the fishes with no or with little modification.

Pinnipeds (harbor seal, bearded seal, walrus) have not been the objects of biological studies (other than as hosts of parasitic worms at Barrow). They are important to the Eskimos and, with the unnatural concentration of people at Barrow in the past two decades, may be under excessive hunting pressure. Some study of the populations is needed.

Cetaceans have been represented by at least five species at Barrow. Ray (1885) talked with Eskimos who had seen narwhals, but they were considered long extinct in Barrow waters in 1883. A Dall's porpoise was taken in an Eskimo gill net in 1952 but it is not clear how often they occur in the area. I observed a beluga foetus among the piles of walrus segments in the village in 1953. The men appeared to be entirely familiar with the beluga, but regarded it as occurring more to the west (and south) and considerably further east; it is not as common as the pinnipeds. These three are the toothed whales.

Two whalebone whales occur commonly at Barrow, the bowhead (Alaskan population of the Greenland right whale) and the gray whale. The most recent comprehensive account of the bowhead dates from the 1860's (Eschricht and Reinhardt 1861). Various aspects of the biology of bowhead and gray are under study by Durham (unpublished manuscript). His study text provides new observations based on more than 30 butcherings, adds new observations on osteology (especially the skull and limb girdles), myology, other soft parts, on various aspects of physiology including the disposition of mass, on embryology and on distribution and population trends. Durham has visited bowhead whaling villages other than Barrow studying bony remains and discussing whale occurrences and practices with the whalers. He has also studied gray whales at Barrow and at Point Richmond, California.

These whales as they occur at Barrow have been characterized by MacIntosh (in conversation) as constituting the greatest single existing opportunity for whale research. In all other situations biologists await the pleasure of those butchering the whales commercially. At commercial shore stations whales are already long dead when they are drawn to the flensing deck; tissues are beyond use for precise biochemical or cytological study. In any case, investigators must be quick, sometimes working almost between slashes of the flenser.

At Barrow, if a serious effort were to be made, it would be possible to organize a shore team and mobile laboratory. In agreement with whalers it is possible to take and draw onto the ice an April or May bowhead, have a scientific team take anatomical, histological, cytological, serological, parasitological samples, and a variety of other materials of quality almost never attained; make all appropriate measurements, and turn over to the village nearly as much of the whale as is taken ordinarily and in not much more than the ordinary amount of working time. A similar beaching of a gray whale during summer would provide a like range of measurements and materials for investigation.

It is not to be supposed that such an effort would all go smoothly, but it is probably reasonable to hope for three generally effective bowhead operations in five whaling seasons. Three such operations when the materials were worked up would increase our detailed knowledge by at least an order of magnitude.

THE DEEP BASIN

Introduction

Study of the basin beyond the shelf has had few options for the scientists. Most operations have been from platforms fixed in slowly and erraticly moving pack ice. Areas of sampling have been restricted. On the other hand there is somewhat more homogeneity of the environment (fewer niches to seek out) than inshore. Much more of the work too can be done by a solitary technician; and very many more man hours with better spread through the seasons were devoted to drifting station work from 1952 to 1955 and from 1959 to the present than to work on the continental shelf. Three sets of plankton samples from an automatic plankton sampler on naval submarines have helped to fill in the picture. Thus the work is in some respects much further along than parallel work on the shelf.

Plankton and Ice-Interface

Horvath (see Mohr 1959) took the first plankton samples from a hydro-igloo on thin (less than 10 ft. or 3 m.) ice at the rim of Fletcher's Ice Island, T-3, at 86°45′ N. in November 1952. He took a number more during 14 months divided among three tours of duty in 1952 to 1955, at the end of which T-3 was over the shelf of Ellesmere Island. English (1961) took part in IGY-drift station Alpha in 1957 and 1958 providing observations on ice-interface communities, photosynthesis and other aspects of plankton, measurements of primary productivity (by chlorophyll *a* and C^{14} techniques), measurements of light energy in open water and under flow-ice and giving useful estimates of amounts of open water in leads. Grice (1962) reported 18 copepod species and their distributions taken by an automatic sampler attached to the submarine *Seadragon* during a polar run. Mohr and Geiger (1962) made comparisons of the general performance of the *Seadragon's* device with that of nets suspended from the drifting stations. Since 1959, teams from University of Southern California, University of Washington, and McGill University have worked on the NARL drift stations; respectively their principal objectives have been: inventory and water-mass indicator organisms, productivity and population analysis, and scattering layer analysis.

Collections to date may be presumed to have taken the macroscopic plankters except those that are quite uncommon or are elusive English's excellent "umbrella nets", collapsible, with mouths several metres square that can be passed through the narrow hydroholes are showing, by catching series of such supposed rarities as bathypelagic proboscis worms (*Dinonemertes*) and liparid fishes, that there is still need for catching gear working in ways different from those we have used.

Most important macroscopic organisms are the copepods. Arctic copepod taxonomy is still inadequately known at least by American workers. Brodskii (1950; Brodskii and Nikitin 1955) has provided the principal taxonomic study of the Calanoidea. Johnson (1956, 1963a, b) has made the most impressive contribution analysing icebreaker collections from the southern border of the Canada Basin, and station Alpha, to about 85° N. Geiger (1966) has noted size variation in one important species. Dunbar and Harding (1968) have related collections made from T-3 in the summer of 1964 in the Beaufort Sea between 80°34′ and 85°53′ N. with principal water masses. Hughes (1968) analysed the distribution of the 8 most common (of 25 species recognized) copepods in the summer of 1966 (apparently about 75-76° N.) and the following winter (*c.* 79° N.) in an area just south of Dunbar and Harding's (1968) stations. His samples were taken with a plankton pump. The copepods being at once the most important and potentially useful for considerations of many sorts — and taxonomically the most difficult — it is very desirable that an updated counterpart of Brodskii's (1950) monograph, with improved figures and keys, be produced.

Of other prominent groups with a number of macroscopic plankters the jellyfishes (medusae, siphonophores and ctenophores) have been studied by Shirley (1966). Dawson (1968) has studied the chaetognaths and an illustrated key to these is being prepared. Knox (1959) studied the T-3 1952-55 pelagic polychaetes; unless new devices such as the English umbrella net show them to be numerous, there is probably no need of a key to them. The rather few taken by University of Southern California drifting station representatives since 1959 have not been worked up. Barnard (1959) reported on the Horvath T-3 amphipods, Tencati and Geiger (1968) have reported on those from the ARLIS II-East Greenland collections; Tencati is preparing an illustrated key to basin species.

With a great part of the foregoing studies, one or more factors reduce the value of the work. Sometimes hydrological determinations parallel to the sampling were not made. Sometimes line capacity did not permit proper depth sampling. Winches were mostly not of a kind or in a condition that permitted controlled operation of nets. Some of the studies, *e.g.* that of Hughes (1968), treat samples from different areas as essentially identical on the hypothesis that populations of a single watermass (in sense of Coachman) are practically homogeneous.

Microplankters as discrete organisms have had little attention from NARL workers. Green (1959) reported on *Globigerina* (which he thought might be benthic) in his study of skeletons in sediments taken north of Ellesmere Island, from 86°45′ N. to the shelf by Horvath (see Mohr 1959) from T-3. Kennett (in press) has demonstrated in an analysis using scan-grams that arctic drift station *Globigerina pachyderma* are distinct from antarctic *G. pachyderma*. Hülsemann (1963) reported on the Horvath T-3 radiolarians and Tibbs (1967) on radiolarians, three tintinnids, *Globigerina*, and unicellular algae (one silicoflagellate and four peridinians) taken from ARLIS I as it moved westward into the influence of Bering Strait (Pacific) water. He noted that the colour of luminescence of the globular peridinian, *Noctiluca*, was different from that of medusae. Keller (1967) has noted changes in the form in *Ceratium arcticum* from different parts of the ARLIS I track.

Of the various University of Southern California field men, only Tibbs (1967) made specific efforts to take protistans. I find no indication of such efforts by other teams. Accordingly, record of protozoans is very inadequate and of unicellular algae, almost entirely lacking. No work was done on bacteria.

Plankton studies of several sorts are needed:

1) A highly standardized series related to previous collections but provided with comprehensive parallel physical data, the samples to be taken with standardized nets at controlled depths, with metered flow at depth, or raised at controlled rates, the positions of the stations being determined precisely.

2) Measurements giving a comprehensive knowledge of light energy available to organisms in leading areas and under principal types of ice cover (with influence of snow cover and without) through the photic zone and through the months of the year with light.

3) Experimentation with a wide range of gear (for example use of various sorts of traps, variations of the collapsible nets) to complete inventory.

4) The taking of microorganisms for inventory, for photosynthesis studies, for physiological and biochemical studies.

5) These studies should be combined in an effort to test Dunbar's (1968) hypothesis that heterotrophic use of dissolved or particulate organic material results in major recycling of materials, and that the high efficiency of chlorophyll-c containing algae in low-light-level photosynthesis (scotosynthesis?) makes it doubtful (Dunbar 1968, p. 39) that even in the Arctic Ocean light is a limiting factor to plant growth. As part of such a study, we are looking into the modification of Yentsch's new submersible plankton pump with packaged power as a means of sampling particles and both very small and ordinary plankters.

6) A range of studies of photosynthesis in leads, under ice, at ice interface, and in mixed and pure cultures of phytoplankton should be undertaken. In these considerable effort should be made to insure that, whether oxygen production, C^{14}, pigment analysis, or ATP, as by Holm-Hansen and Booth (1966) are used, the determinations are comparable to studies made in other latitudes and in the southern hemisphere.

7) The community of the under surface of the floe as an ecological unit has yet to be studied.

8) Although on the drifting ice stations far fewer organisms than at Barrow offer advantages for physiological, biochemical, or biophysical study, and working conditions there are especially unsatisfactory, study of some particularly significant problems should probably be at least begun on the drifting stations where suitable organisms are directly accessible and where some of them may be started toward "domestication"; for instance scotosynthetic algae could be used for controlled light studies, and big-eyed amphipods for behavioural or neurophysiological studies.

9) Drifting station studies should be augmented whenever possible with samplings from icebreakers and particularly from submarines.

Bottom Organisms

The story of bottom work is largely one of inadequacies: for instance winch performance has been inadequate for most stations. The studies of Hunkins *et al.* (1960) and of Menzies (1963) indicate persuasively that the arctic bottom is not rich; Menzies suggests that the Arctic Ocean at 300 m. is about as poor as the Antarctic is at 4,000 m. and contrasts the best Arctic Basin growths with the invertebrate thickets shown in Bullivant's (1959) photographs in the Ross Sea. Green's (1959) account of fall-off of kinds and individuals of foraminiferans taken north of Ellesmere Island remains the most significant south-north transect; and Mohr's (1959) account of marine biological work at T-3, 1952-1955, despite mistakes and incompleteness, and Mohr and Geiger (1968) give a reasonably accurate general impression of the bottom biota as it is now known.

Analysis of the many successful long cores made in 1968 from T-3 should have considerable biological interest. It should provide much evidence on the history of the basin, a subject debated on the basis of very limited materials.

Many more bottom photographs are needed. Ideally at least some of these should be made in conjunction with sampling (as with the Emery-Smith-Campbell grab) of biota and water.

The work on the bottom is so limited that time for dredging (the Menzies small biological trawl has given the best yields of the devices we have used) should be found when the drifting station is moving well, and particularly when rises are encountered. Information is scanty for the slopes of the continental shelf and of the Lomonosov Ridge.

Work on microorganisms, which is a major desideratum even for inventory, will require microbiologists. A specialist or specialists are also needed to work over samples for protozoans and small multicellular animals, as many of these require special attention for study. Observation of both microorganisms and macroscopical groups in life should be attainable and is essential if anything of their roles is to be known.

CONCLUSIONS

Limits

I have indicated that at no sector and level of arctic marine biology are all the obvious tasks finished, nor in many cases has even a beginning been made. Because polar projects are more expensive than ordinary ones, special efforts should be made to screen proposed research designs very carefully for appropriateness and quality, to determine that the investigators are capable and that they are willing to carry the proposed work to fruition.

To find really superior scientists for many of the researches that would bring most credit to NARL and do most to confirm the wisdom of expanding facilities there, it will be necessary to give the scientists some of the amenities they can count on at the laboratories at which they now work (as at Plymouth, Woods Hole or Friday Harbor). These range from prompt, frank, and full responses to correspondence and professional attitudes of support staff, to careful maintenance of equipment. For biology it would certainly be well to have a resident biologist.

Minimally it should be kept in mind that scientists good enough to be appropriate for the new NARL are already busy. It is worthwhile to point out to a number of them the particular advantages of northern work, and to provide those who are convinced with support and courtesy akin to that available at other laboratories so that NARL is not a mainly July and August base for only some superior work.

Benefits

A specific charge of the convener of the Symposium was to state the benefits of marine biological work. The worth of polar studies to science, as far as the work has been or will be good, is great, and appropriate to the cost, because of the exceedingly interesting influences of cold, of light and of the other special conditions of the environment. With better planning, support and integrated build-up of results, it can be more valuable, with more return on investment.

Benefit to supporting agencies I shall not mention now, not because I regard this as unimportant but for quite opposite reasons: partly because support has been borne by too few agencies, partly because the matter requires fuller treatment than is possible here.

To our hosts and neighbours of the Arctic Slope, I think potentialities of benefit are significantly large and I think we may say much of what may be taken from the environment on a sustained yield basis. Observations have been made on changes in Eskimo whaling that could make for retrieval of a significantly larger proportion of whales killed. Whaling, like certain forms of hunting, probably has important value of manly accomplishment beyond calories obtained and may need very much to be continued and protected for social and psychological reasons, but the proteins, fats, and associated vitamins are not negligible. Development of Eskimo ethics of conservation while introducing more effective whaling methods may be a significant benefit that biologists of the laboratory can bring. Some extension of our knowledge of the stocks of shrimps, snails, bivalves, fish, seals, walruses and cetaceans is necessary before we can say how much more protein can (in some cases it may be how much less should) come from the arctic Alaskan sea.

From the marine biologists too should probably come, in cooperation with sanitary engineers, some word on the limits of disposal of community refuse to the sea.

The University of Alaska has certainly gained some glory from having provided a mantle of operation for much good work. However, I must conclude that mutual benefits that could very simply accrue from more frequent interactions between the biologists of College and of NARL have been lacking.

It may be said most sincerely that an early appraisal of living resources, of conditions before modern exploiters use the savagery of sophisticated tools to alter the environment, is one of the most valuable objectives. If, beyond this, the scientists of NARL give an example of sober and economical use of living resources in doing clean and significant scientific work, that will indeed be of benefit to the nation.

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Geology, Especially Geomorphology, of Northern Alaska

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INTRODUCTION

Northern Alaska is considered here to include the geomorphic provinces of the Arctic Mountains, the Arctic Foothills, and the Arctic Coastal Plain (Wahrhaftig 1965). The Arctic Mountains are loosely synonymous with the Brooks Range in the usage of many; the combined provinces of the Arctic Foothills and Arctic Coastal Plain with the Arctic Slope (e.g., Gryc 1958). The gross topography and geologic features of the Arctic Mountains and Foothills may be compared with their counterparts in the Rocky Mountains and fronting plateaus of Canada and the United States.

The Arctic Slope and Brooks Range, for practical purposes, encompass the range of logistic support that is feasible from the Naval Arctic Research Laboratory at Point Barrow. Therefore, the geology with which we are concerned is confined to those provinces. The Coastal Plain, being closest to Point Barrow, is primary.

A field-oriented, isolated laboratory, such as NARL, is obliged to further primarily such research as is peculiar to its environs. Research not so related should be done closer to centres of civilization where costs are lower and where normal operational procedures permit greater efficiencies in the use of man's time. Moreover, federally sponsored research should supplement and complement that being done through private enterprise. It should not compete with nor duplicate unduly the privately funded research.

Because of the frantic exploration for oil at the present time, large sums of private money are being spent on various facets of the bedrock geology of the Arctic Slope and Brooks Range. In view of this, certain constraints should be placed on the immediate goals for geologic research supported by NARL in northern Alaska. This does not mean, of course, that NARL should back away from supporting basic geologic research. A certain amount of overlap is always healthy, especially when it is done for different purposes. Compilation of regional geologic reports and detailed areal mapping have long been the forte of the U.S. Geological Survey and should continue to be so. Nonetheless, the various companies are competing, and funds are too short to duplicate much of their normal, and very expensive, subsurface and geophysical research. Hence, a number of broad but rather well-defined avenues of geologic research assisted by NARL seem blocked out for immediate emphasis.

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For example, certain research in the general field of geomorphology, including glacial and Pleistocene geology, is geographically restricted or topically unique to northern Alaska. Topics in this category are less important to the petroleum companies whose major efforts are devoted to older portions of geologic time. Those portions of geologic history, such as the Precambrian, are also of less concern to the petroleum companies, although the position of the "basement" is of primary concern to them. Clearly, then, the most recent and oldest portions of geologic history fall especially into the domain of NARL at the present time and in the immediate future. So, too, do basic process-oriented studies with no immediate practical goal.

In the following pages a brief description of the provinces of the Arctic Coastal Plain, the Arctic Foothills, and the Arctic Mountains is presented for background. Some representative projects supported by NARL, as related to those provinces, are noted by literature citations. Most abstracts and unpublished manuscripts are omitted. A few general references needed to "round out the picture" are included. Many recent papers, especially on bedrock geology, are omitted, because acknowledgment to NARL specifically was not seen. A list of selected references on the geology of northern and northeastern Alaska is available (Brosgé *et al.* 1969). Finally, some conclusions on the future role of NARL in support of geologic research in northern Alaska are attempted.

GEOLOGIC SUMMARY

Arctic Coastal Plain Province

The Arctic Coastal Plain Province in which Barrow and NARL are located is roughly triangular in shape and extends almost 900 km. from Cape Beaufort on the west to the International Boundary on the east. It reaches its maximum width of about 175 km. due south of Barrow. The Coastal Plain is characterized by low topographic relief (Hussey and Michelson 1966), thousands of lakes and swamps (Black and Barksdale 1949; Carson and Hussey 1962 and 1963), and numerous meandering streams. Drainage is not integrated.

The Coastal Plain is a surface primarily of deposition. The surface sediments of unconsolidated silts and sands with some clays and gravels comprise the primarily marine Gubik Formation of Pleistocene age (Black 1964a). Those sediments rest with slight angular unconformity on marine shale, mudstone, and sandstone of Cretaceous age west of the Colville River and on clastics, particularly red beds, of Tertiary age east of that river (Payne *et al.* 1951). Older rocks underlie the Cretaceous and Tertiary rocks.

The sediments extend northward under the Arctic Ocean with little or no topographic or geologic break. A broad regional arch plunging gently northward extends south from Barrow through the Coastal Plain and into the northern Foothills. Many structural warps lie east of the Colville River. The Precambrian basement near Barrow plunges southward, and the late Paleozoic and Mesozoic rocks on it thicken southward.

A characteristic tundra plant assemblage varies in composition from place to place, depending on the composition, texture, and drainage of the sediments (Britton 1957; Spetzman 1959; Wiggins and Thomas 1962). Eolian features are widespread (Black 1951a).

Continuous permafrost and low relief result generally in poor drainage over large areas and in the development of striking patterned ground (Black 1952 and 1963; Tedrow 1962), of thermokarst phenomena (Anderson and Hussey 1963; Black 1969), and of various ice-cored mounds (Black 1951b). The lake area of some 65,000 sq. km. is perhaps the most unique feature of the Arctic Coastal Plain Province. Tens of thousands of lakes are unusually well oriented with their long axes a few degrees west of north. The lakes range in length from a few metres to 15 km. Shapes may be described as elliptical, triangular, ovoid, egg-shaped, rectangular, and irregular.

Arctic Foothills Province

The Arctic Foothills Province lies between the Arctic Coastal Plain to the north and the Arctic Mountains to the south. The province may be subdivided into northern and southern units, each with affinities closely related to the province it adjoins. It is bounded on the north in places with distinct topographic break. To the west of the Colville River that boundary is a marine notch that lies generally between 160 and 200 m. above sea level; to the east of the Colville River it reaches a maximum elevation above sea level of about 400 m. The boundary in places is a zone as much as 35 km. wide. On the south a major topographic break, commonly over 1,000 m. above sea level, occurs at the steep front of the Arctic Mountains.

The northern part of the Foothills is characterized by broad, rounded east-trending ridges, dominated only locally by mesa-like uplands. The higher southern part is characterized by much greater relief, as much as 800 m., and by numerous irregular buttes, mesas, and long linear ridges with intervening undulating plains and plateaus. The Foothills are dominated by erosional topography which emphasizes and is etched from the east-trending open folds of the Cretaceous sedimentary rocks in the northern part and of Devonian to Cretaceous sedimentary rocks and of intrusions all tightly folded and overthrust northward in the southern part. The lowlands are cut mostly in shale; the higher features are held up by more resistant sandstone, conglomerate, limestone, and chert. The Cretaceous-Tertiary rocks almost everywhere cross the north border without break except in degree of folding. They are very gently inclined in the Coastal Plain and broadly folded in the northern Foothills. At the south border the softer Mesozoic rocks, especially shales, generally lie within the Foothills Province and the older more resistant rocks form the steep front of the Arctic Mountains. The structural complexity is shared.

The drainage of the Foothills is integrated. Major streams originating in the Brooks Range are structurally controlled by and in part superposed on the bedrock. The Colville River, the largest, trends easterly for more than 300 km. in part along the somewhat arbitrary boundary between the northern and southern parts of the Province before turning abruptly north near Umiat. Most streams are swift yet portions are braided across gravel flats locally covered in winter with thick river icings. Spring break-up is a time of flooding and channel shifting. Only a few thaw lakes and lakes of unknown origin exist.

Arctic Mountains Province

The Arctic Mountains Province contains a variety of topographic forms which may be divided into several sections (Wahrhaftig 1965). Although lowlands exist along some major rivers, the gross topography can be called mountainous; it is rugged and complex. Several deeply dissected and glaciated mountain ranges represent the offset extension of the Rocky Mountains. Relief generally is 1,000 to 2,000 m. Elevations of 1,600 to 2,500 m. are common for peaks, and valleys are incised to elevations of 1,000 to 1,300 m. Both general elevation and relief increase eastward, but no low passes cross the eastern part. Accordant summit elevations differ in local ranges.

Sedimentary rocks of Paleozoic and Mesozoic age are intricately folded, extensively faulted, intruded, and locally metamorphosed. East-striking Devonian and Mississippian rocks are exposed almost continuously through a sequence of over 3,500 m. A thick clastic sequence covers carbonates in the northern part of the province (Gryc *et al.* 1967); northward overthrust plates in imbricate arrangement are the major structural feature. These have been etched in strong relief by streams and glaciers. Limestone of Silurian age and metamorphic rocks of earlier Paleozoic and probable Precambrian age occupy the southern part of the province. The northern border broadly coincides with the boundary of the Mesozoic and Paleozoic rocks.

East of the 149th meridian the province bulges northward to within about 40 km. of the Arctic Ocean. Folds and thrust faults continue to trend eastward so greater uplift seems apparent. Major orogenies in early Cretaceous, Tertiary, and Quaternary times are recognized.

During the Pleistocene, glaciers enlarged at different times in the mountains and flowed northward onto the southern part of the Foothills and southward into the interior of Alaska. Drainage derangements are common. Drainage divides migrated markedly during the Pleistocene. Streams today flow outward from the mountains; the Noatak River bisects the western part of the Range. The major lowlands contain numerous small lakes. Larger rock-basin and morainal-dammed lakes are scattered throughout the province, but are more abundant in the eastern part. Small glaciers are still found in the higher areas.

TOPICAL REVIEW OF NARL-SPONSORED RESEARCH

From the time of the earliest explorers up to 1944 only reconnaissance studies could be carried out along the coast and major rivers. Nonetheless, the gross framework of the geology of northern Alaska was established during the decades prior to the establishment of the Naval Arctic Research Laboratory. From 1944 to 1953 the Department of the Navy, through the Office of Naval Petroleum and Oil Shale Reserves funded numerous United States Geological Survey parties in northern Alaska, with special emphasis on Naval Petroleum Reserve No. 4. Several of the parties received direct support from NARL. The reader is referred especially to United States Geological Survey Professional Papers 302 to 305, in their many parts, for examples of the studies which Reed (1958) reviewed in considerable detail.

Results from some of the U.S. Geological Survey's studies are found also in publications other than those of the Survey, such as Brosgé *et al.* (1962); Tailleur and Sable (1963), and Gryc *et al.* (1967). Regretfully, it is not always clear what role the NARL played in furthering some of the basic geologic studies in northern Alaska from which numerous reports of the Geological Survey scientists were derived.

NARL-supported research on the bedrock geology of northern Alaska outside that of the Geological Survey has been limited. Two outstanding contributions on regional geology come quickly to mind — Porter (1966a) in the central Brooks Range and Reed (1968) in the northeastern Brooks Range. Each mapped and described the very thick Paleozoic and Paleozoic-Mesozoic sequence of rocks in his area and summarized the deformational history. In each report a review of the available literature provides an up-to-date source of information for representative portions of the Arctic Mountains. Langenheim *et al.* (1960) carried out a more specifically oriented study on Cretaceous amber from the Arctic Coastal Plain. Insect and floral remains embedded in the amber were stressed.

The various bedrock studies have done much to place that aspect of the geology of northern Alaska on firm ground and have provided the background that made possible the recent oil strikes in the Prudhoe area southeast of Barrow.

Geomorphology

Most bedrock studies were focused largely on a resolution of the stratigraphy, sedimentation, paleontology, tectonics, and other facets of geology ultimately geared to assess the petroleum possibilities of northern Alaska; of necessity, surface morphology and surficial materials generally were relegated secondary roles by the scientists involved in those studies. Obviously all geologists use geomorphology in their surface mapping and to help in interpreting subsurface geology, but by only a few or in certain places could geomorphology be studied for its own sake. Furthermore, traverses were made primarily to locate bedrock outcrops, and surficial materials were hindrances. Nonetheless, all U.S. Geological Survey field parties made pertinent observations on the unconsolidated materials, as exemplified in part in the summary assembled by Black (1964a). Notes on the topography and morphology of various features also accompanied most regional reports.

Without question a list of the most striking geomorphic features in northern Alaska would be headed either by the oriented lakes or by the ice-wedge polygons. Both features are a consequence of permafrost, or perennially frozen ground, that extends to depths of 400 m. in northern Alaska (Black 1954). Both phenomena were recognized and described prior to the inception of the Arctic Research Laboratory (e.g., Black and Barksdale 1949; Leffingwell 1919). However, the early descriptions only whetted the appetites of researchers who followed. I believe I am correct in saying that NARL has supported more research projects in earth science, including soils, that relate directly or indirectly to those two phenomena than to any others. This is rightly so in the opinion of this writer, for those two phenomena reach their zenith in the vicinity of Barrow.

THE ORIENTED LAKES

In permafrost regions thaw of ground ice, which comprises more volume than pore space in unconsolidated sediments, results in thaw depressions that may become lakes. Both thaw depressions and thaw lakes are circum-Arctic and are exceedingly abundant. The oriented lakes of the Arctic Coastal Plain not only typify such thaw depressions with lakes, but they epitomize the orienting capabilities of the prevailing winds.

Black and Barksdale (1949) suggested that orientation was by wind oriented at right angles to that of today. None of the subsequent investigators has accepted that suggestion. Deevey (1953) thought it probable that elongation and migration of the lakes took place at right angles to the prevailing wind. Livingstone (1954) first called attention to a possible mechanism whereby currents account for the elongation of the lakes at right angles to the present winds. Rosenfeld and Hussey (1958) pointed out that the problem was more complicated than the simplified approach of Livingstone, and that his hypothesis could not apply equally to lakes only a few metres long and those many kilometres long. They suggested an elongation control by fault and joint patterns. Carson and Hussey (1959) reviewed five possible hypotheses for the lake orientation and concluded that each alone was not enough, but that a composite would suffice, namely: that oriented ice wedges might develop in a fracture system and maximum insolation would be more effective in melting the north-south trending wedges than the complementary set, and that the depressions so oriented would be perpetuated and enlarged by thaw and wind (wave) oriented sediments deposited on the east-west shores. Carlson *et al.* (1959) also suggested that preferentially oriented ice wedges play a role in the orientation of the lakes.

Carson and Hussey (1960a) reviewed the hypothesis of Livingstone (1954) and an unpublished one by R. W. Rex and then presented some current measurements from lakes near Barrow. Their field data suggested that Livingstone's hypothesis was not applicable but that the approach of Rex merited further study. Carson and Hussey (1960b) provided additional data on the hydrodynamics in three of the lakes near Barrow. Their measurements showed that erosion was going on at the ends of the elongated lakes by long-shore currents as predicted by the hypothesis later published by Rex (1961). Carson and Hussey (1962) summarized the results of their field studies on the lakes and supported with reservations on some aspects the circulation hypothesis of Rex (1961). Price (1963) raised the wind-resultant problem, but Carson and Hussey (1963) concluded that it would not change materially their earlier conclusions. Britton (1957) outlined a thaw lake cycle and its association or effects on vegetation on the Arctic Coastal Plain. Maps showing overlapping lake basins of different ages were prepared by many of the authors cited above and by Wahrhaftig (1965) and Brown and Johnson (1966).

Dating the lake basins, except in relation to each other, has been difficult. All observers of the lakes have witnessed shore erosion of several metres during single storms. Lateral migration can be very rapid. The truncation of existing ice wedges by lateral migration demonstrates that some lakes or parts of them must only be some decades or a few centuries old. Livingstone *et al.* (1958) used the growth rings of small willows to show that the gentle shore of one oriented lake was exposed during the last 150 years. Radiocarbon dating of organic matter in two drained lakes near Barrow suggested ages of several thousand years (Brown 1965). Carson (1968) concluded that transgressive expansion reached a maximum between 4,000 and 8,000 years ago. Other lakes must be considerably older according to the great depth to which thaw of permafrost has penetrated.

Not all lakes have been derived by thaw of ground ice (Mohr *et al.* 1961) although the studies of Brown (1966a), Hussey and Michelson (1966), and Black (1969) indicated that thaw depressions 3 to 6 m. deep can be produced from the thaw of ice in the upper part of permafrost today. Livingstone *et al.* (1958) cited a particular instance of supposedly much greater thaw. The origins of the deep lake basins in the Arctic Coastal Plain and Arctic Foothills are not known.

Brown *et al.* (1968) discussed the hydrology of a drainage basin near Barrow. Brewer (1958) outlined the thermal regime of a lake near Barrow. The mineral compositions of some drainage waters from lakes, streams, and elsewhere in northern Alaska were reported by Brown *et al.* (1962). Effects of an arctic environment on the origin and development of freshwater lakes in northern Alaska were treated at some length by Livingstone *et al.* (1958) and the limnology of the arctic lakes was summarized by Livingstone (1963). Kalff (1967, 1968) added more limnological information. Black (1969) reviewed thaw depressions and thaw lakes of North America, especially those of northern Alaska.

PATTERNED GROUND

Patterned ground includes a variety of surface forms many of which are related to frost action and permafrost (Washburn 1956). A widespread pattern in part characteristic of continuous permafrost is produced by ice wedges in polygonal array as seen from above (Black 1952; Péwé 1966). The ice-wedge polygons of the Arctic Coastal Plain are ubiquitous and reach a climax of development in association with the oriented lakes. Only in a few restricted areas of the world have other polygons even begun to emulate those of the Arctic Coastal Plain.

The distribution, character, and origin of the ice wedges of the Arctic Slope were established decades ago with remarkable insight by Leffingwell (1919). Leffingwell's contraction theory for origin of ice wedges calls for present-day segregation of ice in ice wedges after the ground is frozen to considerable depth and for the moisture to come from the atmosphere. However, Taber (1943) working elsewhere in Alaska cast doubt on Leffingwell's findings. Taber's concept is that the ice wedges and other large masses of ice grew in the past when the permafrost was forming and that the moisture was drawn up from below the downward freezing layer. Black (1963) initiated a project at Barrow in 1945 to resolve the opposing theories of those men. He and his uncomplaining wife, Hernelda, at times under difficult and trying weather conditions, and with direct support from NARL in 1949-50 did the detailed laboratory and field studies needed to establish the correctness and to quantify the theory of Leffingwell.

Black's studies involved observations in all parts of Alaska with ice wedges, but the critical laboratory studies of thin sections of ice and the detailed field measurements of thermal contraction and expansion of the ground were done at Barrow with support from the facilities of NARL. Ground ice collected at Fairbanks was even packed in dry ice and carried back to Barrow. Thermal measurements, meteorological records, moisture and textural determinations, and many other data were collected during the studies. A resumé of the studies and a list of the published results derived directly from them is included in Black (1963).

No one has repeated the detailed fabric studies of ground ice or the measurements of ground contraction and growth of ice wedges, although supplementary and partial confirmatory observations have been made by a number of investigators in the course of their studies. For example Lachenbruch (1962 and 1966) placed the mechanics of thermal contraction cracks and ice-wedge polygons on a firm mathematical-physical foundation; Brown (1966b) investigated the chemistry of ice wedges and related frozen ground; Drew and Tedrow (1962) proposed a classification of ice-wedge polygons; O'Sullivan (1966) expanded the chemical studies of permafrost in the Barrow area; and Walker and Arnborg (1966) related ice wedges and other ground ice to river-bank erosion. A large number of papers on the relationship of soils and vegetation to patterned ground in northern Alaska have appeared; Black (1964b) has reviewed a number of them. More recent papers include Brown and Johnson (1965) on pedoecological investigations at Barrow; MacNamara and Tedrow (1966) on an arctic equivalent of the Grumusol; Tedrow (1966) on arctic soils in general, but northern Alaska samples in particular; Brown (1966c) on soils of the Okpilak River region of northeast Alaska; Brown (1967) on tundra soils formed over ice wedges near Barrow; Tedrow and Brown (1968) on soils of arctic Alaska; Rickert and Tedrow (1967) on soils in aeolian deposits of the Arctic Coastal Plain; and Tedrow (1968) or the pedogenic gradients of the polar regions.

GLACIAL GEOLOGY

NARL supported a number of the U.S. Geological Survey geologists who made unusual efforts to record geomorphic data, including glacial geology, which were published in separate reports, e.g., MacCarthy (1958) on glacial boulders on the Arctic Coast; Sable (1961) on the Okpilak Glacier in the northeastern Arctic Mountains. Other projects supported by NARL on geomorphology and glacial geology entirely or at least as a major part of a field project include, for example, Hamilton (1965, 1969) on geomorphology and glacial geology in the Alatna River area of south-central Brooks Range; Porter (1966b) on the Pleistocene geology of Anaktuvuk Pass in the central Brooks Range; and Reed (1968) in northeastern Brooks Range. As our understanding of Pleistocene-Recent chronology of events has grown in North America, so too has our understanding of events in northern Alaska (Detterman *et al.* 1958). Each of the above authors recognized events not previously recorded and each revised the correlation of glaciations and other events from those of previous workers in their areas. Hamilton (1969), Porter (1966b) and Reed (1968) provide correlation charts and literature citations for all previous glacial literature pertaining to the Arctic Mountains. General agreement on the gross framework of the Pleistocene-Recent events seems to have materialized rapidly over the past 15 years.

MISCELLANEOUS

In close association with the glacial studies are pollen-stratigraphic attempts to work out changes of vegetation which permit correlations with former climatic changes. Livingstone (1955) in particular established a three-zone pollen-stratigraphic record for the central Brooks Range, and later (1957) he extended the study northward onto the Arctic Foothills. The radiocarbon-dated stratigraphy and pollen sequence correlated well with the latter part of the glacial sequence. Colinvaux (1964), with samples supplied by others on NARL projects, showed that vegetation of 14,000 years ago reflected a climate colder than the present and that progressive warming extends to the present day. This record indicated that the Arctic Ocean has been covered with ice since the time of the Wisconsin glacial maximum. The Arctic Ocean ice cover apparently has been continuous for at least the last 1.5 million years according to Clark (see pp. 233-45).

Radiocarbon dating of buried peat and other organic matter in the upper part of permafrost has done much in the past few years to substantiate and also to revise our thinking of the rapidity of geomorphic events in northern Alaska. NARL has sponsored a number of studies which have yielded reports specifically on the dating of various events, for example, Péwé and Church (1962) on the age of the Point Barrow spit; Porter (1964) on the antiquity of man at Anaktuvuk Pass; Tedrow and Walton (1964) on the age of the glacial deposits of the upper Killik Valley; Hume (1965) on the sea-level changes during the last 2,000 years at Point Barrow; Brown and Sellmann (1966) on a buried peat from sea level at Barrow, and Faas (1966) on estuarine sediments at Barrow. Brown (1965) compiled a summary of all known dates from the vicinity of Barrow that were acquired in support of various studies in pedology, geology, and archeology. He draws a number of conclusions from the dated materials, e.g.: 1) the majority of soils and surficial features around Barrow are no older than 8,300 years and are perhaps considerably younger; 2) the present-day spit sediments are about 1,100 years old; 3) the upper section of the next inland raised beach is not older than 25,000 years and may be considerably younger; 4) a surface horizon of well-drained soil on that beach yields an average date of 3,000 years; and 5) buried organic materials at depths of 0.3 to 1.0 m. represent surface horizons of soils that existed some 8,700 to 10,700 years ago.

Other miscellaneous studies include MacCarthy (1953) on recent changes in the shoreline near Barrow; Hume and Schalk (1964) on the effects of ice-push on arctic beaches; Rex (1964) and Hume and Schalk (1967) on shoreline processes at Barrow; Black (1952), Hopkins *et al.* (1955) and Hussey (1962) on airphoto interpretation; Geist (unpublished manuscript) on collecting Pleistocene fossils and natural history material in arctic Alaska river basins; Hanna (1956) on the land and freshwater mollusks of the Arctic Slope; Schmidt and Sellmann (1966) on Pleistocene mummified ostracods near Barrow; Schalk and Hume (1962) on shoreline investigations at Barrow; Hume (1964) on floating sand and pebbles near Barrow; Walker (1967) on dunes in the Colville Delta; and Walker and Morgan (1964) on weather and river bank erosion.

Near-shore, shallow-water studies off Barrow have provided information on various geomorphic processes e.g. Carsola (1954a) on the extent of glaciation on the continental shelf; Carsola (1954b) on the submarine canyons on the Arctic Slope; Carsola (1954c) on the microrelief on the upper continental slope in the Arctic Ocean; Carsola (1954d) on the Recent marine sediments on the continental shelf and slope; and Rex (1955) on microrelief produced by sea ice grounding near Barrow. Numerous raised beaches well inland and submerged topographic breaks, peat, and other submerged deposits attest to numerous fluctuations of land and sea and migrations of the strand line.

CONCLUSION

An attempt has been made to categorize the general geomorphic studies in northern Alaska. The artificial grouping does not permit the recording of numerous geomorphic observations included incidentally in many reports, nor does this review do justice to some major reports on file at the library of NARL but not published. Some have attempted to summarize all or at least many regional and topical aspects, including processes, of the geomorphology of northern Alaska.

STATUS OF GEOLOGIC RESEARCH AND FUTURE ROLE OF NARL

The titles of several papers presented elsewhere in this issue of *Arctic* overlap the general range of geology, especially geomorphology. Subjects such as pedology, botany, oceanography, archeology, permafrost, ecology, sedimentation, arctic engineering, heat flow, geophysics, and even zoology play a role in increasing our knowledge of the earth's surface and our understanding of earth history. Obviously, in the space available, it has been impossible to summarize fully all the major aspects of the subject. I have therefore limited my discussion arbitrarily to only a small part of the studies concerned with the bedrock of northern Alaska, and subsequently, at greater length, with the morphometry and evolution of the surface.

Since its inception in 1947, NARL has obviously played an important and enviable role in furthering geologic research in northern Alaska. Partly through its aid the general bedrock geology has been mapped on a small scale, and regional correlations of the various stratigraphic units have been completed. These and more specific studies of paleontology, texture and lithology, tectonics, paleogeography, and the like, have provided the understanding that has permitted the recent productive drilling for oil and gas.

It seems clear that for the immediate future various oil companies will dominate in the more detailed geologic studies needed to further oil exploration, and that NARL's role in that aspect will be minimal. However, the geologic history of northern Alaska is long and involved. Although they appear dissimilar, the Arctic Mountains are intimately related to the Arctic Slope. During the middle Paleozoic, northern Alaska was the site of a seaway that extended southward from the ancient continent of "Arctica" in what is now the Arctic Ocean. That landmass until Jurassic time shed its wastes southward into the area of what is now northern Alaska. Then "Arctica" began to subside. The southern part of the seaway began to rise, and the ancestral Arctic Mountains were born. Repeated uplifts and folding affected the range and to a lesser extent the Arctic Slope throughout the remainder of the Mesozoic Era, still further restricting the ancient seaway. Meanwhile, thousands of metres of sand, mud, and coal were laid down in the shoaling water. Even volcanoes were active in the region at the beginning of later Cretaceous time.

Thus the landscape, as we see it today, is only the latest culmination of a long and complicated series of events. Working out all the fascinating details will be too much for practical-minded business men who have to have an immediate return on the invested dollar. Various areas of bedrock geology will still remain — for example, studies of paleontologic, mineralogic, and near-surface facies changes of the younger rocks in the Arctic Coastal Plain and the Arctic Plateaus will very likely need support. In the Arctic Mountains some detailed stratigraphic mapping, tectonics, metamorphism, and the like will go begging. A number of excellent Ph.D. thesis topics for the individualistic field-oriented geologist should be supported, perhaps in conjunction with funds from private companies. The regional compilations of the U.S. Geological Survey should continue along with their areal mapping.

NARL seems destined to emphasize geomorphic research with all its broad implications. Regional studies are still needed, but topically oriented and process-oriented research should lead. Such research can go on from its present base, on the oriented lakes, patterned ground, weathering and soil formation, pingos and other mounds, eolian activity, slope processes, glacial geology, etc. Almost no study made to date provides final answers: each has opened more possibilities. Only a few topics need be cited here.

The general characteristics and distribution of the oriented lakes are recognized, but many details are not. Some or at least parts of the shallow shelves surrounding the deep central portion of some oriented lakes are depositional and some erosional. Truncated ice wedges are found under some shallow lakes and shallow shelves. They seem to reflect a recent development of those lakes and shelves. Some shallow lakes lack deep central basins. Are they the incipient lakes in contrast to the deeper ones that have thawed through the wedges? Are the shallow lakes all younger than the deeper ones? New wedges are growing on the floors of drained lakes and on the abandoned beaches of others We seem to have a vast range in age of lakes and lake basins, but relatively little information is at hand.

Few definitive limnological studies on the oriented lakes have been attempted, and almost no bottom sediment studies. Even the lake orientation still poses problems although more effort possibly has gone into that facet than into any other. At present it is difficult to distinguish between cause and effect in the circulation patterns of the lakes. Fetch and water depth obviously determine what waves and currents can do. In many lakes the north and south ends have deep water and the banks are eroding. The two-cell circulation system demonstrated for several elongate lakes may be the cause, but how can we make the transition from the very small equal-dimensional lake or from the large very shallow lake in which waves and currents are not effective transporting agents? The shallow shelves, whether erosional or depositional, seem mostly to be on the east and west sides; many lakes are enlarging also in those directions.

Timing of the formation of lakes in the past is essentially unknown. The overlapping basins show clearly a relative chronology, and buried deposits of former lakes are found at depths of many metres, some in association with buried fossil ice wedges. A long and complicated history of events can only be hinted at now.

Growth rates of ice wedges in northern Alaska have been measured for only one year and only at Barrow. The available radiocarbon dates support the dating of surfaces with ice wedges, but obviously a longer interval of time is needed to get average rates under present climates in different parts of northern Alaska. Relatively few wedges and samples of permafrost have been studied for their microscopic fabrics or their chemistry, and all these were from the immediate vicinity of Barrow. More regional coverage is needed. Quantification of the cryostatic processes in the active layer is desperately needed. Studies of weathering in association with the patterned ground and soil formation have been going on, but much more detailed quantification of the process with time is now required.

Although general agreement seems to have been reached in the glacial sequence in the Arctic Mountains, many areas remain to be mapped in detail. No comprehensive glaciological studies of individual glaciers have been attempted. Miscorrelations of deposits of relatively youthful age with pre-Wisconsinan events have been made. It seems unlikely that knobby moraine with undrained depressions and ponds in fine-grained deposits could survive from early Pleistocene times along the front of the Arctic Mountains as has been postulated. Eolian activity, mass wasting, frost processes, and vegetal growth should have destroyed them. Many more detailed studies specifically to do glacial geology and to resolve some of these problems are timely. If accompanied by quantified studies of slope processes, a better appreciation of the rate and manner of evolution of the landscape could be obtained.

To my knowledge no detailed study of river icings in northern Alaska has ever been made, yet that area has the "most" and the "best" in Alaska. The eolian deposits have largely been ignored. Marine erosion since the days of the early explorers has amounted to tens of kilometres in some places. Other than a few observations and some extrapolations from air photos and the like, few recent studies of its rate along the Arctic Coastal Plain have been attempted. Numerous raised beaches and submerged topographic breaks, peat, and other deposits attest to considerable migration of the shore line, not just in recent times, but extending back through the Pleistocene into still older chapters of earth history.

These are but a few examples in present processes and in earth history that NARL should support enthusiastically. It is true that alpine geomorphology can and is being studied in such places as Colorado which are much closer to centres of civilization than are the Arctic Mountains. Nonetheless, the 30° of latitude intervening, the different rocks, and unlike histories of events make for differences in kinds or intensity of processes which only detailed measurements can document adequately.

The Arctic Mountains have been shedding their wastes across the Foothills and Coastal Plain at different rates for a long time. Most rocks in northern Alaska are marine. Vast changes in the elevation of land and sea are thus recorded in the deposits and features of northern Alaska, and only a glimpse of that fascinating history has been obtained to date. We must continue to study together those processes, features, and deposits on shore as much as those off shore — they are part of the same continuum of earth history. In other words, the United States Navy must continue to support research in its back yard while playing in its front yard.

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Heat Flow in the Arctic[1]

ARTHUR H. LACHENBRUCH AND B. VAUGHN MARSHALL[2]

INTRODUCTION

Heat is continually escaping across the earth's surface because the interior is relatively warm, and heat flows by conduction from warm regions to cooler ones. This flux at the earth's solid surface of heat conducted from the interior is referred to in geophysics as "heat flow." Other things being equal, the more rapidly the temperature increases with depth (i.e., the greater the thermal gradient), the more rapid the heat flow. On the other hand, if the gradient is constant, the heat flow is more rapid, the greater the thermal conductivity. Generally, the amount of heat flow is equal to the product of these two quantities, thermal conductivity and thermal gradient. In order to measure the heat flow, it is necessary to measure them both.

How great is heat flow? Generally, on the order of one-millionth of a calorie escapes through each square centimetre of the earth's surface every second. (The unit will be called hfu for "heat-flow unit.") This is about enough to melt a 4-mm. layer of ice over the earth's surface each year. It is less by almost four orders of magnitude than the flux received by the earth from the sun. Hence, it has no detectable effect on the earth's surface temperature and, contrary to a widely held view, cannot generally be detected by airborne or satellite infrared measurements. Although this energy seems small, the amount leaving the earth in one month is approximately equal to the energy equivalent of the world's annual coal or oil production, and it exceeds by perhaps two orders of magnitude the rate of energy dissipation by the earth through volcanic or seismic processes.

Where does this earth heat originate? Certainly much of it must come from the decay of radioactive uranium, thorium, and potassium which occur in minute amounts in virtually all earth materials. It is likely that roughly half of the flux from the continents is contributed by these materials concentrated in the thick crust. The remainder must come from the underlying mantle. The thin crust of the ocean basins contains relatively small amounts of radioactive elements, and it could contribute no more than 5 or 10 per cent of the surface flux. It is known, however, that the heat flow from the ocean basins is not significantly different from that from the continents; therefore, much more heat must be flowing from the mantle beneath the oceans than from the mantle beneath the continents. Within the ocean basins and within the continents, both the surface flux and the distribution of crustal heat sources vary significantly. It is important to understand these variations, because they represent differences in temperature, physical state, and composition of underlying materials, and variations in the distribution of energy available for the work done by the earth in building its mountains and possibly drifting its continents.

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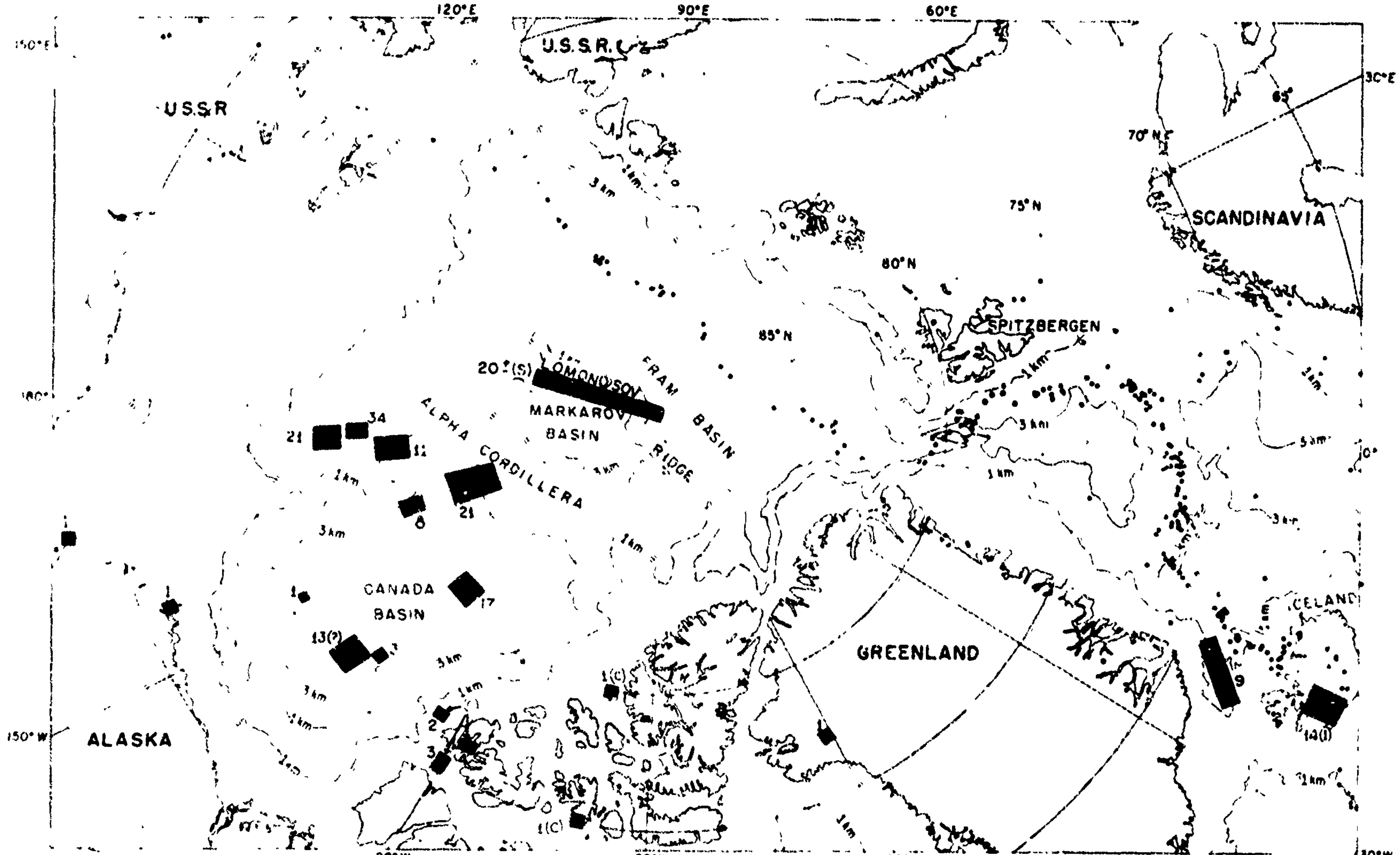

FIG. 1. Approximate location of heat-flow observations in the Arctic. Numbers indicate approximate number of measurements made in adjacent black quadrilaterals. Measurements by Soviet, Canadian and Icelandic scientists are denoted respectively by (S), (C) and (I). Dots deno'z seismic epicenters (Sykes 1965).

HEAT FLOW ON LAND

Fig. 1 illustrates the present distribution of heat-flow measurements in the arctic regions. Within this area there are only two published values of heat flow measured on land. One is at Cape Thompson, Alaska (Lachenbruch *et al.* 1966) and the other is at Resolute, Cornwallis Island, Northwest Territories (Misener 1955). The value at Cape Thompson is close to the world-wide average of 1.5 hfu, and the correct value at Cornwallis Island is probably somewhat less (Lachenbruch 1957). Shown also in Fig. 1 are two measurements determined from gradients in ice caps; one by Paterson (1968) on Meighen Island and the other by Hansen and Langway (1966) on Greenland. Although such measurements are uncertain because of the effects of ice accumulation and mass movement, both give reasonable values in the neighbourhood of 1 hfu. Several measurements on Iceland by Pálmason (1967) were made in shallow boreholes and are uncertain because of the effects of water movements. However, they generally suggest a high heat flow, well above 2 hfu, which is not surprising for this volcanic island situated athwart the mid-ocean rift system. The value shown for Barrow (Lachenbruch and Brewer 1959) is uncertain but probably close to the world-wide average. With these sparse and uncertain measurements, it is clear that no regional interpretation of land heat-flow patterns is yet possible in the Arctic. However, careful study of some of these geothermal results yields insight into problems peculiar to arctic heat-flow measurements and provides supplementary information of considerable interest concerning permafrost, climatic change and shoreline movements.

Fig. 2 shows measured temperature profiles from three boreholes at separate localities along the Alaskan arctic coast. Although the gradients vary by a factor

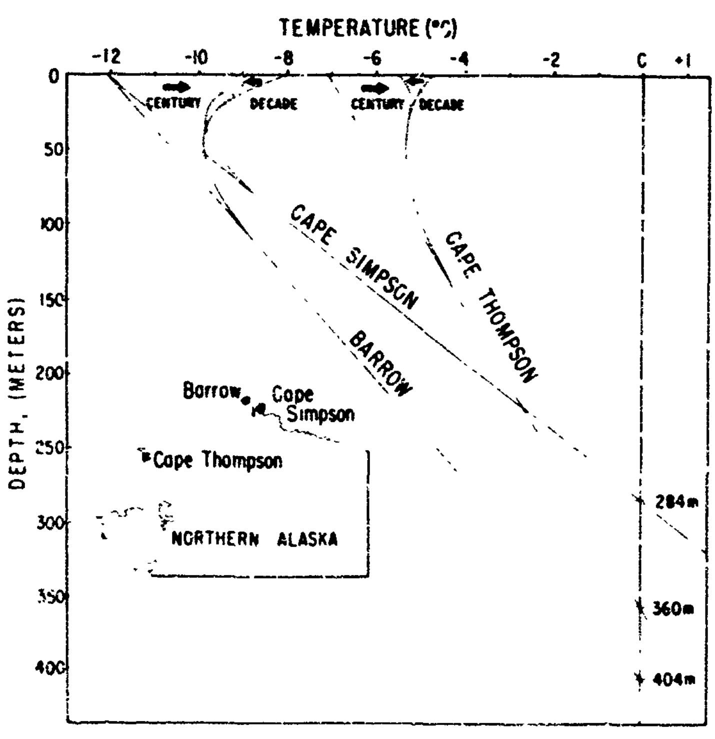

FIG. 2. Temperatures measured at three locations in arctic Alaska (solid lines). Extrapolations are shown as broken lines.

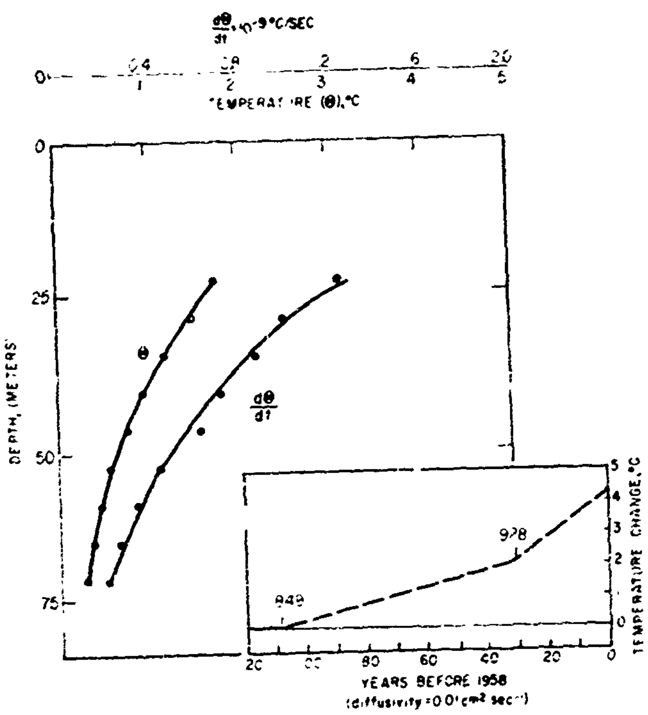

FIG. 3. Reconstruction of history of mean ground surface temperature from measurements in a well near Barrow, Alaska (dashed curve). Corresponding theoretically determined temperature anomaly, Θ, and its rate of change dΘ/dt (solid-line curves) are compared with measured values (dots) in upper graph.

of two, the heat flow at all three sites is probably within 10 per cent of the world-wide average. In other words, the gradient variations are evidently due to compensating variations in thermal conductivity. The danger of estimating permafrost depth from surface temperature alone is evident from this illustration. At Cape Thompson the surface temperature is 4°C. warmer than it is at Cape Simpson, but permafrost there is 76 m. deeper.

In areas of continuous permafrost, ground water is generally immobile and heat conduction theory can be applied to the analysis of earth temperatures up to within a few feet of the surface. The curvature in the upper 100 m. or so of the three curves in Fig. 2 clearly represents a climatic warming. The linear portions of these profiles represent thermal equilibrium established with a surface temperature determined by upward extrapolation to zero depth. Evidently Cape Simpson and Barrow formerly had a mean surface temperature of about −12.1°C. and this must have obtained, on the average, for many thousands of years. At Cape Thompson the long-term mean surface temperature was about −7.1°C. The change in surface temperature responsible for the warming of the upper 100 m. can be reconstructed approximately by heat-conduction theory (see e.g. Birch 1948). Such a reconstruction for the Barrow well is shown in Fig. 3. Because temperature observations were made in this well over a period of 8 years, it was actually possible to observe the rate of temperature change as a function of depth in addition to the total temperature anomaly (inset, Fig. 3). The broken line represents a theoretical reconstruction of the temperature change, and the solid curves show the anomaly it would produce. Hence the mean annual surface temperature at Barrow must have increased more than 4°C. since the middle of the nineteenth century. As the initial temperature was −12°C., the final temperature must have been about −8°C. However, the present mean surface

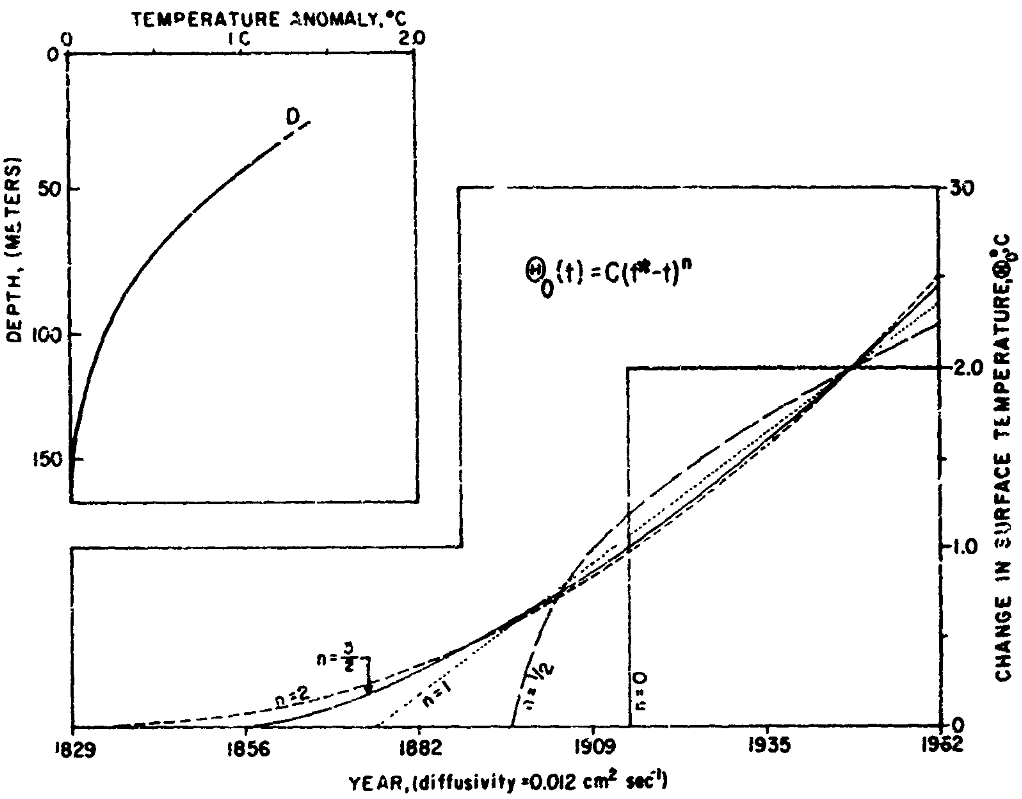

FIG. 4. Reconstructions of history of surface temperature, Θ_0, from measurements in a well near Cape Thompson, Alaska. All curves in lower graph are consistent with observed temperature anomaly shown on upper graph. (t^* —t) is time since start of climatic change; C and n are adjustable parameters.

temperature at Barrow is somewhat lower, about −9°C. (Lachenbruch *et al.* 1962). Therefore, a more recent cooling must have taken place, one that has not yet had time to penetrate to the depth of the shallowest measurement, which is on the order of 30 m. Such a cooling could hardly have been in progress more than a decade or so. A similar analysis at Cape Thompson (without information regarding the rate of cooling) is shown in Fig. 4. It is seen that the change is synchronous with the one in Barrow, although somewhat smaller. The mean surface temperature at Cape Thompson is again lower than the temperature predicted by the analysis, and a much more recent cooling is also indicated there.

It is clear that any attempt to make heat-flow measurements in this region from gradients determined in the upper 100 m. would fail, as these gradients would not represent steady flux from the earth's interior. Nevertheless these climatic perturbations give information that is interesting in itself.

More important than the climatic change to arctic heat-flow measurements is the effect of bodies of water in regions of continuous permafrost. There the mean temperature of the emergent surface may be −5 to −15°C., in striking contrast to the bottoms of bodies of water that do not freeze to the bottom where the mean temperature is close to 0°C. The result is that near such shorelines large amounts of heat enter the solid earth from beneath the water body and emerge again nearby. Such heat is easily mistaken for heat originating in the earth's interior. The

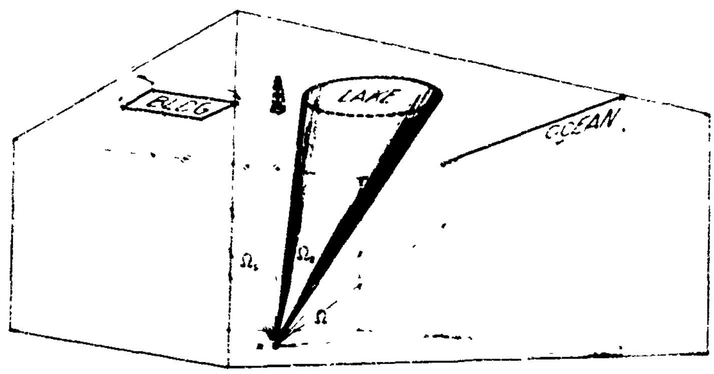

FIG. 5. Subsurface temperature effect of regions of anomalous surface temperature. Steady-state disturbance at any point, P, is the sum of solid angles (Ω) subtended by anomalous regions weighted by the anomalous temperature in each.

subsurface temperature effects of the warm spots beneath bodies of water are illustrated by the solid angle relations of Fig. 5. Their effects on permafrost distribution are shown in Fig. 6. The upper right-hand curve of Fig. 7 shows the measured temperatures at Resolute, Northwest Territories, at a point 365 m. from the ocean, and 460 m. from a large lake. The lower left-hand curve shows the profile corrected for these bodies of water. Evidently more than half of the heat flowing to the surface at the Resolute borehole entered the earth beneath the adjacent bodies of water. The heat flow there, which was originally interpreted as being almost twice the world average, is evidently somewhat lower than the world average.

Although thermal effects of water bodies can cause problems in arctic heat-flow measurements, they can supply information about the history of such bodies of water, as derived from measurements of the depth of permafrost. In two holes near Cape Thompson, one 120 m. from the shore and the other 1,200 m. from the shore, it was possible to estimate that the shoreline moved in to its present position about 4,000 years ago, Fig. 8 (Lachenbruch *et al.* 1966). A correction for latent heat effects increases the estimate to 6,000 years; a value consistent with archeological evidence (Giddings 1960).

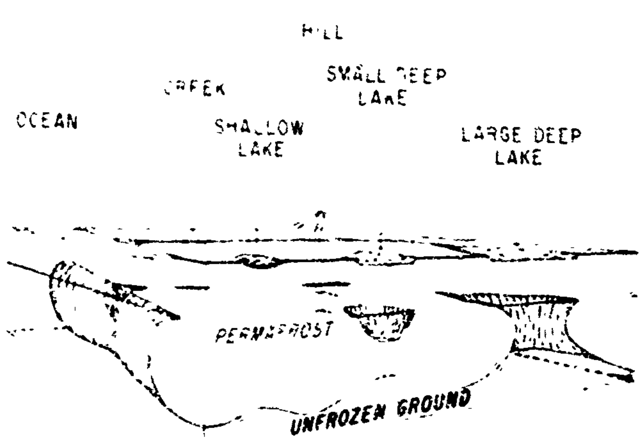

FIG. 6. Schematic representation of relation between surface features and permafrost distribution. "Deep lakes" do not freeze to bottom, "shallow lakes" do. Shown for mean ocean temperature greater than 0°C. (e.g., Cape Thompson, Alaska). For mean ocean temperature less than 0°C. (e.g., Barrow, Alaska), see Lachenbruch 1957, Fig. 4.

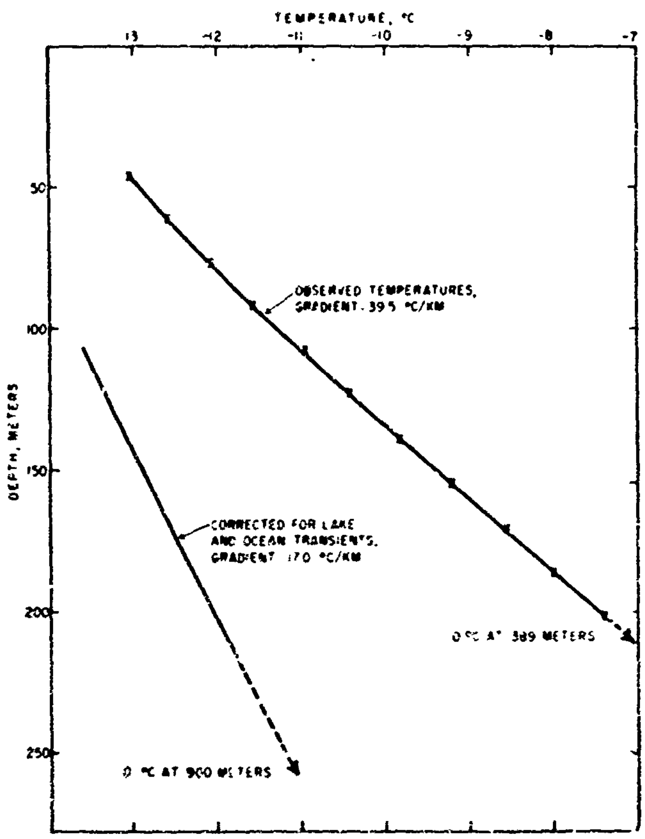

FIG. 7. Correction of observed temperatures for thermal effects of near-by bodies of water and shoreline regression in well at Resolute, N.W.T.

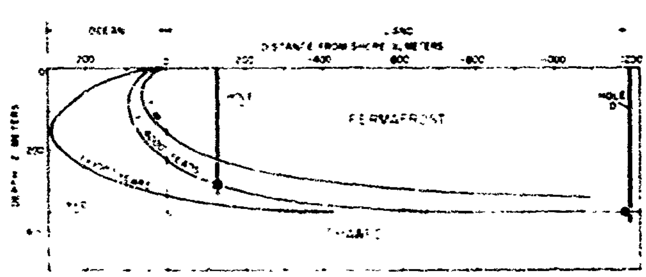

FIG. 8. Permafrost distribution near Cape Thompson, Alaska, computed for a rapid shoreline transgression t years ago; effects of latent heat neglected. Curve t = 4,000 yrs. bp close to present condition although time since transgression probably greater (see text). Asterisks denote measured depth of permafrost.

OCEANIC HEAT FLOW

The problem of measuring the two fundamental quantities, thermal conductivity and gradient, required for a heat-flow measurement is, strangely enough, much simpler in the ocean basins than on the land. This is primarily because ocean-bottom temperatures are generally quite stable, and it is only necessary to measure gradients to depths of a few metres in the bottom sediment to obtain steady-state values. Typical data are shown in Fig. 9 for one station on the Canada Abyssal Plain and a nearby one on the Alpha Rise. The conductivities determined from cores at the rise station are substantially higher than those from the station on the plain, but this effect is more than offset by the high gradient on the plain where the heat-flow value is much greater. The agreement of component heat flows over 1-metre intervals attests to the stability of the thermal conditions at depths of only a few metres. Although such conditions are typical of deep ocean,

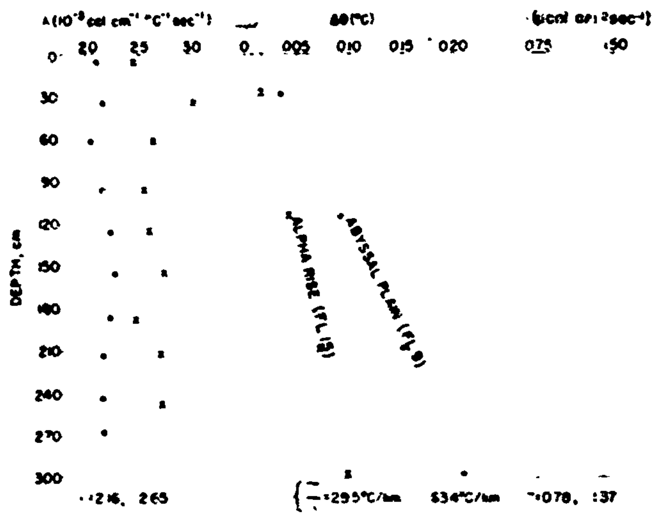

FIG. 9. Typical thermal results from the floor of the Canada Basin (solid lines and dots) and the Alpha Rise (broken lines and x's). K is thermal conductivity, $\Delta\Theta$ is sediment temperature less sea-bottom temperature, and q is heat flow.

they are not universal, particularly where the water depth does not exceed 2 km. This is illustrated by the nonlinear profiles from Denmark Strait (Fig. 10). These curvatures, like those shown previously for northern Alaska (Fig. 2) are the result of fluctuating surface temperatures; in this case, temperature changes at the ocean bottom on a time scale varying from a few hours to several weeks. Like the effects of climatic change on land, these perturbations provide information of considerable significance. In this case they reveal a previously undetected pattern of bottom-water oscillations with a period of a few weeks and a wave length of a few hundred kilometres (Lachenbruch and Marshall 1968). Analysis of the linear portions of these profiles yields a simple picture of decreasing heat flow along the traverse. As before, study of the complications in the thermal picture yields information with independent value.

The approximate locations of heat-flow measurements made in the Arctic Ocean as of this time are shown in Fig. 1. The region denoted with an (S) is the approximate position of the measurements obtained from a Soviet drifting station. The values obtained there have not been reported in detail, but they evidently tend to be above the world average (E. Lubimova, written communication and oral presentation at IUGG Heat-Flow Symposium, Zurich, Switzerland, 1967). The values denoted with a (C) were obtained through the ice in shallow water by scientists from the Dominion Observatory, Ottawa (Law *et al.* 1965; Paterson

FIG. 10. Sediment temperatures beneath about 1 km. of water in Denmark Strait. Numbers on curves designate stations.

and Law, 1966). Values between the islands are close to the world average, and those farther off shore are much lower. The other oceanic values were obtained from drifting ice stations by the U.S. Geological Survey in cooperation with the Office of Naval Research. The measurements north of Iceland (from ARLIS II) confirm high heat flow near the mid-ocean rift system and suggest that the heat flow falls to normal values over a distance on the order of 100 km. (Lachenbruch and Marshall 1968). It is seen that the remainder of the measurements are in the Alaskan quadrant of the Arctic Ocean. No information is available from the large region of east longitude which is bisected by the mid-ocean rift system. This system is delineated by the dots on Fig. 1 which denote seismic epicenters (Sykes 1965).

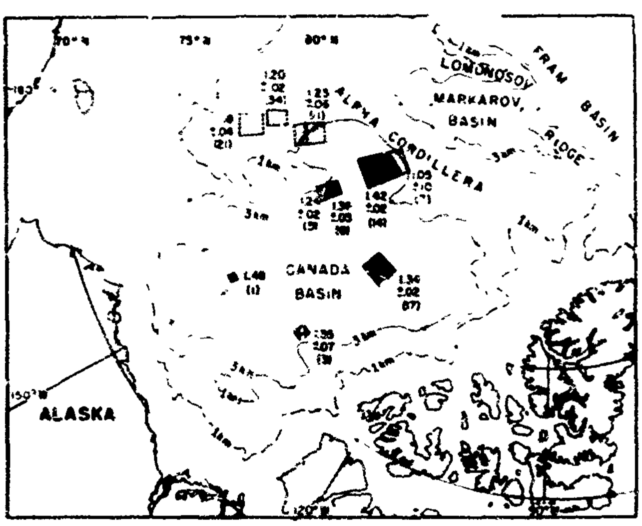

FIG. 11. U.S. Geological Survey heat-flow results from Alaska quadrant, Arctic Ocean. Three-digit number is average heat flow, number preceded by ± is standard error and number in parentheses is number of observations represented. Water depth is greater than 3500 m. in blackened regions, less than 3500 m. in crosshatched regions.

In Fig. 11 the results from the Alaskan quadrant are shown in greater detail. Measurements in the blackened regions were made beneath water more than 3,500 m. deep; in crosshatched regions water depths were less than 3,500 m. A cursory inspection shows that the shallower water stations generally yield a somewhat lower heat flow. The contrast in heat flow across the edge of the basin has been analysed in detail in the quadrangle at 83°N. (Fig. 11). The sharp change in heat flow observed at the edge of the Alpha Rise seems to require a lateral discontinuity in thermal conductivity across the entire crust. One interpretation suggests that the low-conductivity upland crust projects out tens of kilometres under the adjacent basin (Fig. 12). The model is inconsistent with previous views of the Alpha Rise, namely that it is mantle material or a lagging remnant of a foundering continent. It is consistent with the view that the rise is a great accumulation of basalt such as might be expected in an extinct mid-ocean ridge (Lachenbruch and Marshall 1966); this view is now supported by magnetic observations (King *et al.* 1966; Ostenso and Wold 1967). An alternative interpretation of the heat-flow anomaly, namely that it is caused by a deep dike parallel to the rise axis, is also consistent with this view (Lachenbruch and Marshall 1966).

Returning to the systematic difference between heat flow in the basin and on the adjacent uplands, we note the bimodel distribution in the histogram of Fig. 13.

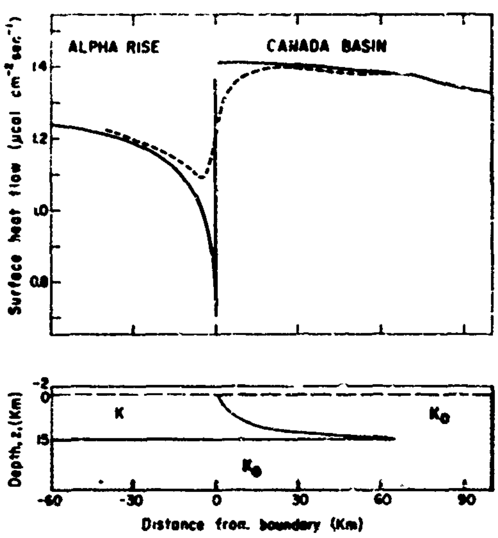

FIG. 12. Geothermal model of the Canada Basin-Alpha Rise boundary. Thermal conductivity in unshaded portion (K) is one-half that in shaded portion (K_0). Solid and dashed curves in upper graph represent theoretical heat flow for ocean bottom at $z = 0$ and $z = -2$ km. respectively. These two models bracket heat-flow observations.

The lower part of Fig. 13 shows that the heat flow from the deep basin is roughly 15 per cent greater, and considerably more uniform, than that in the surrounding regions. As these mean values have standard errors of only about 1 per cent the difference, about 0.2 hfu, is quite significant. It is substantially greater than the amount of heat that could be generated in the thin oceanic crust beneath the deep basins. Hence, these data suggest that the average heat flow from the mantle beneath the basin exceeds the average heat flow from the surface in the surround-

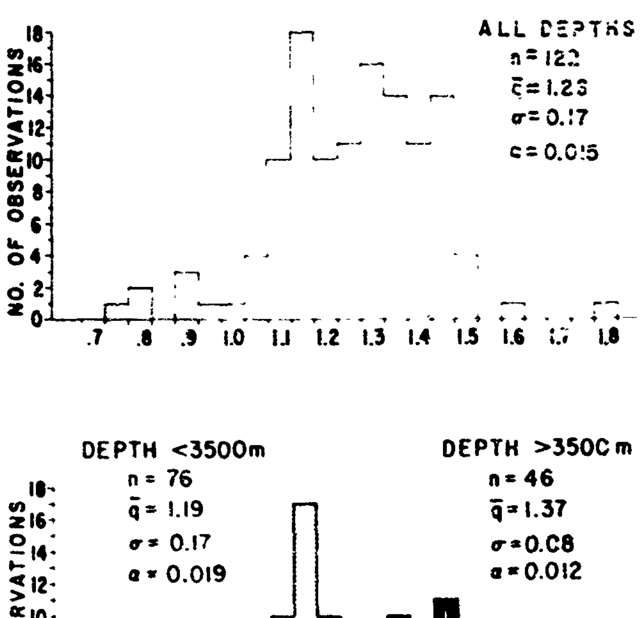

FIG. 13. Histogram of heat-flow observation shown in Fig. 11. Shading represents depths less than 3,500 m.; cross-hatching represents depths greater than 3,500 m.; n is number of samples, $\bar{q}$ is mean heat flow, σ is standard deviation, and α is standard error.

ing highlands. The mantles must be significantly different beneath these contrasting tectonic units.

FUTURE HEAT-FLOW STUDIES IN THE ARCTIC

Because of substantial logistic problems associated with field studies in arctic regions, it is obvious that arctic research should focus on those problem areas in which the Arctic offers a unique advantage. On the land, it is necessary in the future to increase greatly the number of heat-flow measurements so that we may delineate patterns and the relationship of heat flow to major tectonic provinces. Judging from experience in better-known areas, we might expect such information to lead to a more basic understanding of the geologically-observed tectonic contrasts.

It has been pointed out that regions of continuous permafrost offer a unique opportunity to apply simple conduction models to within a few feet of the surface. A fruitful area for future research will be to apply such models to geothermal data from permafrost to obtain accurate reconstructions of climatic fluctuations occurring over the past few centuries. The relation of such fluctuations to various environmental factors such as ice conditions in the Arctic Ocean are of particular interest, as they may yield insight into the mechanisms responsible for ice ages.

The remarkably large temperature difference between bodies of water and emergent surfaces at high latitudes provides opportunities to investigate shoreline fluctuations over the past 10,000 years by geothermal techniques. It might be rewarding to exploit this opportunity as the amount of near-shore drilling increases with economic development of the Arctic.

From the point of view of geothermal studies, the Arctic Ocean region is exceptional in two respects: 1) Much of it is accessible for very closely-spaced equilibrium observations at reasonable cost from stations on the ice, and 2) it contains a miniature ocean, smaller by an order of magnitude than the major oceans of the world. Over a relatively small area this ocean contains a great variety of sharply delineated features including what appear to be typical oceanic abyssal plains, a seismically-active mid-ocean ridge, two aseismic oceanic ridges of different types, and an assortment of continental slopes and shelves. These two unusual features make the Arctic Ocean an excellent place for detailed studies of the geothermal field within and at the boundaries of major crust — upper mantle units. Specifically it is particularly desirable to extend the heat-flow coverage to regions of east longitude and the vicinity of the arctic rift system.

Because the ice drifts more slowly by an order of magnitude than a vessel on the open sea, it provides a unique opportunity for very careful measurements of the temperature structure of the water and sediment very close to the ocean bottom. Further studies of this important interface are needed for an understanding of problems related to solid-earth heat flow and to physical oceanography.

Wherever geothermal studies are carried out, their value will be greatly enhanced by simultaneous observation of other geophysical quantities and by precise navigation and bathymetry in ocean areas as well as by regional geologic studies on the land.

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Arctic Engineering for the Seventies: A Philosophy

CHARLES E. BEHLKE[1]

In the past the Naval Arctic Research Laboratory has been a base of operations primarily for biological and physical scientists and has only occasionally functioned as a base for engineering research. In spite of the sparsity of engineering research performed at the Laboratory, the results have been significant. Harold Peyton's sea ice studies, carried out over a period of four years, have provided him with the knowledge necessary for him to give important advice on the designing of many of the Cook Inlet oil drilling platforms which have made possible the beginnings of the State of Alaska's leap into world prominence as a petroleum giant. The benefits of his research work at NARL during the late 1950's and early 1960's are today proving to be of major value as the Northwest Passage concept for super tankers is pursued.

In the autumn and winter of 1968, Pipe Line Technologists, Inc. in conjunction with University of Alaska engineers, directed by Professor George Knight, located a large pipe 40 inches in diameter and 1,000 feet in length near NARL for the purpose of studying the effects of permafrost on a petroleum pipe and of the pipe on the permafrost. This work is continuing at present and will certainly provide many of the criteria necessary for the design and construction of the giant of pipelines in the western world: the Trans Alaska pipeline. This project has been essentially a group effort on the part of Pipe Line Technologists, the University of Alaska, and NARL.

Having briefly discussed some of the very significant engineering research which has been carried on at NARL, I would like to philosophize for a time about arctic research. It must be borne in mind that the philosophy is that of an engineer, with regard to engineering research, and though I feel it may apply to other research — in the physical and biological sciences — professionals in some of those areas will probably not agree with me.

Recently I attended the Arctic Institute of North America's Symposium on Arctic Transportation held at Montreal. Though I found the conference extremely stimulating, I was continually appalled by the northern transportation engineering questions being posed by arctic experts from Washington and Ottawa. It was painfully obvious that so many of the experts involved in arctic programs had really not lived for very long in the country in which they profess so much interest. They actually have only a professional interest and not a living interest in the North. They and their families do not daily come to grips with the real problems of that part of the world and they and their families do not reap the fabulous personal rewards of the North. They play golf on the weekends, their children play

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football, father and son perform the loud, often exasperating ritual of watching the program on television each Sunday afternoon. So, though their professional work has to do with the North, it is seldom *in* the north and certainly their *lives* evolve around more southerly climes than that place which Robert Service spoke of as, "the great, big broad land way up yonder".

I am convinced that in the area of arctic engineering research it is absolutely necessary for the investigator, together with his family, to live in the North. After all, engineering is nothing more than problem-solving, and how can an engineer know the real extent of arctic problems if he does not acquire that true appreciation of the Arctic that is best developed by living in it, battling it, enjoying it himself. I believe that, as Alaska and northern Canada leap boldly forth into world economic prominence, the immense quantity of engineering research that must be performed in the next several years can only be performed by engineers who live daily with the problems they are attempting to solve. The magnificent new Naval Arctic Research Laboratory is certainly destined to implement this philosophy by being one of the prominent catalysts for bringing arctic engineers and arctic problems more closely together.

Now let me, having philosophized probably too much, indicate very briefly a few areas in which I feel significant engineering research must be performed and in which NARL will undoubtedly play a dominant role. Before men and families can live, as opposed to exist, in the North, it is necessary that better housing be available. We have attempted historically to use California architectural techniques, and materials, with some modifications, for latitudes of 60° and 70°. This has obviously resulted in expensive and inferior housing. Were it possible to construct a 1,200-square-foot home at Barrow for the same price per square foot as that of the new laboratory, it would cost approximately $50,000. Certainly such a home would be extremely modest by more southerly standards. Those of us who live in the North are well aware that protected space to spread out in, particularly during darker winter months, is much more necessary here than in more temperate climates.

Obviously then, vast engineering and architectural research work must be embarked upon in an attempt to find better, more suitable designs, and more appropriate materials together with much less costly fabrication methods. NARL is an ideal base for these engineering and architectural efforts.

Recent oil discoveries in arctic Alaska and the promise of even more significant discoveries in arctic Canada, have suddenly brought renewed interest in the Northwest Passage. There is, of course, one flaw to the Northwest Passage: sea ice. If the super tanker tests planned for the summer of 1969 show the route to be feasible, 250,000-ton ice-breaking tankers will undoubtedly be constructed for year-round operation through the Northwest Passage. Such questions as large ship structural requirements, power requirements, most-economic routings taking into account distances and ease of passage, mooring requirements, oil spill difficulties, must each be studied. Though there are, perhaps, those who at present feel they have solutions to most of these problems, engineering experience shows that when a new venture of this uniqueness initially becomes operational, unanticipated, significant problems arise and the previously anticipated problems become dwarfed in significance. Certainly NARL and the super ships will provide excellent bases of operations for the study of and the solutions to problems associated with the very broad areas which I have indicated.

Lying ahead is more basic work on the physical and chemical properties of sea ice, perhaps with some emphasis on the possibilities of chemically changing some of the ice's physical properties; a better definition of the significance to shipping of various types of ice conditions is also needed. Finally, even the psychological factors involved in the operation of extremely large ships under unbelievably adverse weather and ice conditions during virtually continuous night should also prove to be boundlessly exciting. These problems represent difficult challenges for NARL-based arctic engineers over the next several decades.

Such problems as I have posed cannot be solved at desks, but will require combinations of field and analytical work. The existence of NARL at Barrow will continue to make it possible for the engineer and scientist to perform his field work in the Arctic, but the new structure will make more attractive the performance of the analytic work in the same area as the natural laboratory. Harking back to my earlier plea, it will keep the engineer and the problem much closer together during all phases of study and should result in satisfactory solutions to the pressing, real arctic engineering problems of the next several generations.

Physiological Research in Northern Alaska

G. EDGAR FOLK, JR.[1]

Considering field physiology as a whole, long and continued search for information about the Arctic might be classified informally as: I. The Pemmican and Scurvy Period; II. The Birdskin and Plantpress Period, and III. The Experimental Period. In naming the third period I am trying to create a picture of a third wave of workers moving to and over the Arctic Slope with their slide rules and telethermometers.

One cannot separate the accomplishments of these three periods of work nor limit them in time (Table 1). For instance, the Pemmican and Scurvy Period is still with us today; at the time of writing, this can be illustrated by the British Trans-Arctic Expedition of 1968-69 which is in Class I., yet Wally Herbert and his team also belong in the Experimental Period because they are collecting physiological data.

Table 1. Key Dates in Arctic Physiological Research, Canada and U.S.A.

1881	International Polar Expedition 1881-1883 (Lieut. P. H. Ray).
1913	Canadian Arctic Expedition 1913-1918 (Vilhjalmur Stefansson).
1917	University of Alaska founded.
1921	First journey for physiological anthropology (Levine).
1947	Arctic Research Laboratory established at Barrow (U.S. Navy).
1947	Arctic Aeromedical Laboratory established at Fairbanks (U.S. Air Force).
1948	Arctic Health Research Center established by U.S. Public Health Service.
1952	Ice islands manned by NARL.
1958	Aircraft began to be used extensively by NARL for oceanographic, gravimetric, magnetic and biological research.
1963	Institute of Arctic Biology opened at University of Alaska.
1963	Inuvik Research Laboratory established.

One of the early explorers who had an interest in physiology was Lieutenant P. H. Ray: during his 1881 expedition he made nutritional observations on the Eskimos at Point Barrow. Nutting (1893) is an example of a naturalist of the Birdskin Period with physiological interests. His expeditions were motivated by the hope of discovering the physiological stimulus for the migration of birds to areas thousands of miles to the south; his hypothesis and data on wind direction were new and substantial.

Stefansson, who by 1918 had spent five and a half years on the arctic ice pack and tundra, has been called a nutritionist and physiologist; he had received his training at the University of Iowa. The next author to publish definitively on arctic physiology was Levine (1937) whose first expedition began shortly after

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the founding of the University of Alaska (1917). Later he made ten more expeditions above the Arctic Circle, collecting samples for studies on the nutrition of native peoples; he introduced an important area of work which he named "Physiological Anthropology". His point of view has influenced every anthropology department in the country. Levine, called "Vitamin Vic" by his friends, had a sparkling personality; his genius resulted in 200 papers being published in his lifetime. His field studies were launched from Omaha, Nebraska.

Laboratory-based research work began at Barrow in the 1940's. What types of scientists were responsible for this invasion of a land formerly dominated by whalers, fur traders, oilmen and construction workers? Were they physiologists? The early publications in 1948 by M. C. Shelesnyalk included surveys of the work of all types of scientists including those who worked on such topics as polar ice and oceanography. Apparently (to add a competitive note) *physiological* work was undertaken earlier: Laurence Irving in 1942 published a paper on carbon monoxide in snow houses and tents. He also wrote a review in 1948 of the biological investigations at Point Barrow. Irving's research party was followed by others, resulting in a continuous stream of published physiological investigations from Point Barrow since the mid-1940's. Some of the types of information obtained are listed in Table 2. In each of these physiological areas substantial publications have been completed in separate projects by about four scientists. Their presence at the Naval Arctic Research Laboratory represented considerable bustle since most of them brought research assistants and graduate students for

Table 2. Physiological Studies on the Arctic Slope.*

Mammals	
Blood Analyses	Levine, Musacchia, Wilber and Musacchia (1948), Allison.
Nutrition	Stefansson, Levine, Rodahl, Drury, Milan.
Energy Metabolism	Levine, Irving, Hanson, Fisher.
Fat Metabolism	Stefansson, Levine and Wilber (1949), Irving, Pitts, Wilber, Rodahl.
Circulation	University of Iowa Team (Folk *et al.* 1966).
Temperature Regulation	Irving, Scholander, Hock, Strecker and Morrison (1952), Milan (1962), Henshaw.
Animal Navigation and Sounds	Griffin, Schmidt-Koenig, Poulter, Mellen.
Eye Physiology	Janes (1966), Scholander, Iowa Team.
Reproductive Physiology	Musacchia, Hart, Mayer.
Biological Clocks	Lobban, Iowa Team, Andrews *et al.* (1968), Boland.
Bird Physiology	
Nutrition	Irving, West, Cade.
Temperature Regulation	Irving, West, Gessaman.
Photoperiodism	Nutting (1893), Farner.
Soil Organisms	
Growth of Bacteria	Boyd.
Plant Physiology	
Photosynthesis in continuous light	Tieszen.

* If no date is given, the author's works may be found in *Arctic Bibliography*.

training. Many of these students have returned to work on their own projects, and some of the topics, which are listed in Table 2, deserve special comment: 1) Blood analyses for vitamin content or for blood group studies; much of the large body of data accumulated resulted from work initiated by that colourful researcher, Victor Levine; 2) Nutritional data were obtained from both native peoples and military personnel stationed in the Arctic so that the caloric cost of living in a hostile environment could be described; Stefansson made many contributions in the field of arctic nutrition, as did Rodahl; 3) Energy metabolism is typified by attempts to determine the difference between the basal metabolism of natives and non-natives, and by the present-day exciting and fundamental work on the metabolic turnover of cesium and strontium, by Hanson (see Palmer and Hanson *et al.* 1963); 4) Fat metabolism will always receive much research attention because of the high fat diet in the Arctic (Rodahl and Issekutz 1965); one intriguing question is whether the Eskimos can eat only fat without demonstrating ketosis; 5) Temperature regulation obviously represents the most important physiological topic in the Arctic (Irving 1948); 6) Studies on animal navigation were introduced by Griffin (1952), and exciting data have been contributed by Poulter and others more recently on the communication of sea mammals under the ice; 7) Studies on eye physiology, which lead to an understanding of snow blindness, were introduced by Janes *et al.* (1966) and by Scholander; 8) Very early studies on reproductive physiology were begun by Musacchia (1954) on arctic and temperate zone animals because of the obvious question as to whether continuous light and the extreme cold on the Arctic Slope would alter the reproductive cycles of a species of mammals also found much farther south; 9) Investigations on the measurement of time by animals are often referred to as studies of biological clocks; Mary Lobban (1958), at an early date, realized the possibility of a real alteration or confusion of man's biological clock by the action of continuous light; she introduced definitive and basic studies on natives at the Point Barrow laboratory in 1956 showing that their physiological clock was different from that of people in the temperate zone. Similar work was done on non-natives (Lewis and Masterton 1955) and white rats (Folk 1959). I have limited these remarks to work on mammals but comparable information has been obtained in the areas of bird physiology, microbiology and plant physiology.

Following are some examples of the types of physiological data obtained. Fig. 1 illustrates a very grumpy-looking grizzly bear that carries a radio-capsule in his body cavity to broadcast body temperature and heart rate during the long winter months when he is taking a vacation from life's problems by going into dormancy (Folk *et al.* 1966). From this animal and seven others (including black bears and polar bears) came proof that bears in winter dens show more of the characteristics of true hibernation than was formerly believed (Figs. 2, 3 and 4).

Several months after the polar bears in Fig. 2 were photographed, two new radio capsules were placed in them; these transmitted physiological data for one year and 1.5 years respectively. During the third summer and winter of carrying radio capsules, each of the bears weighed approximately 570 pounds.

The same order of results as those shown in Fig. 3 were obtained on three black bears and two other grizzly bears. During the winter of 1968-69, similar data

FIG. 1. Five-year-old grizzly bear, repeatedly studied with radio capsules. For three summers and winters this animal carried Iowa Implantable EKG and Body Temperature Capsules. During the winter of 1968-69 it also carried three blood flow transducers. In spite of the presence of this electronic gear, not to mention the surgical operations, the bear weighs 670 pounds.

FIG. 2. Two polar bears carrying radio capsules at two years of age. One is unconscious from ether anesthesia, and the other bear is anxiously attempting to awaken it by licking its mouth.

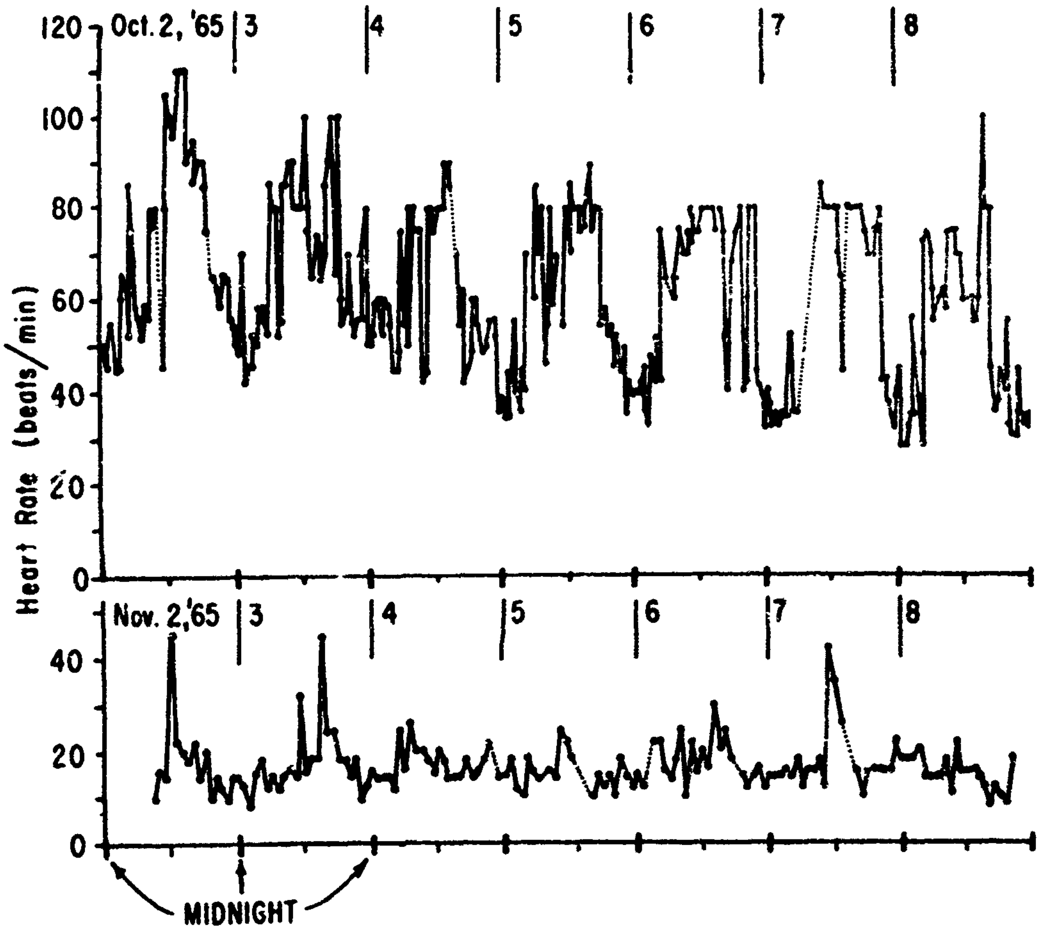

FIG. 3. Heart rates recorded daily every 30 minutes showing the dormancy stages as arctic grizzly bear ('Blondie') went into winter-den condition. Sleeping heart rates began at 40 b/m, became 30 b/m, and by November, 8-10 b/m.

were obtained from the polar bears. One polar bear showed minimum sleeping heart rates of 60 b/m in June, July, August and September. During the month of February the bears were in conditions appropriate for dormancy and the heart rate of the bear which had shown summer minimum rates of 60 b/m gradually dropped until 27 b/m was observed during sleep. On other nights a rate of 30 b/m was common. Undoubtedly the heart rate would have decreased further except that the radio capsule failed at that point.

Fig. 5 illustrates the radio-transmitter itself; Fig. 6 gives the record obtained. An arctic fox (Fig. 7), carrying an internal physiological transmitter which lasted for six months, contributed information on how he tolerates the extreme cold −55°F. (−49°C.) in midwinter; this information also explains how he manages his behaviour patterns when there is a change from the winter's total lack of sunlight to continuous daylight in the summer. (What does a *nocturnal* animal do when there is no period of darkness?) The next two illustrations (Figs. 8, 9) concern eye physiology studied at NARL; these are funduscopic pictures of the backs of the eyes of two red foxes, one lives at Point Barrow and the other lives in Iowa. This technique permits a search for a protective layer of pigment for the arctic

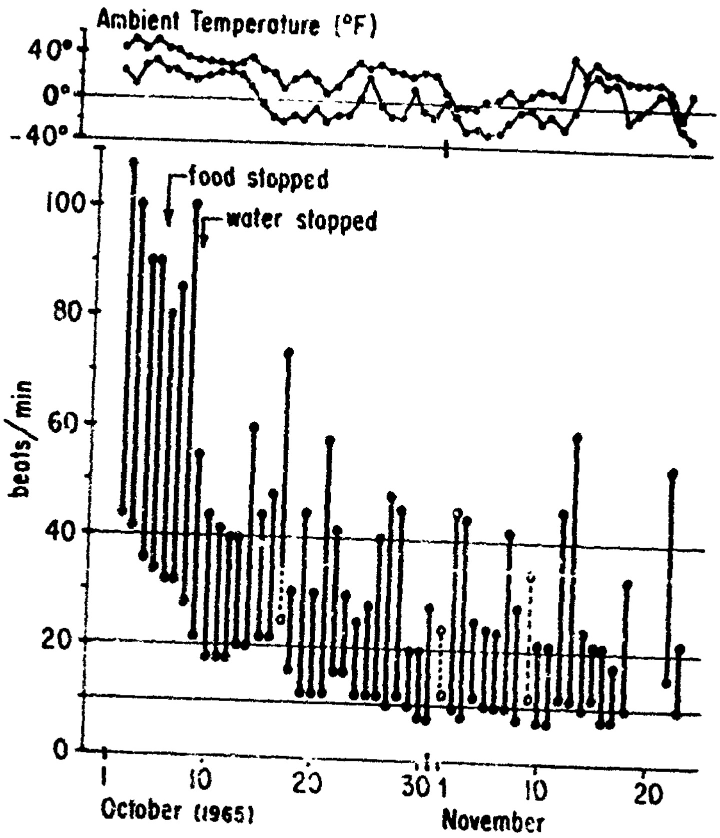

FIG. 4. Combined maximum and minimum daily heart rates during onset of dormancy in the grizzly bear described in Fig. 3. Most daily values were selected (maximum-minimum) from half-hourly readings (48 readings per day). Where vertical lines are dashed, some data were lost, but readings were selected from at least 30 observations per day.

FIG. 5. Small EKG radio capsule with a battery life of six months weighing 16 grams. The two loops are stainless steel electrodes which touch the ventral body wall after the capsule is sewed in the peritoneal cavity. Note at bottom the mercury battery of the type used in electric wrist watches. There is no evidence that any of the animals with implanted radio capsules are aware of the presence of the instruments in their body cavities.

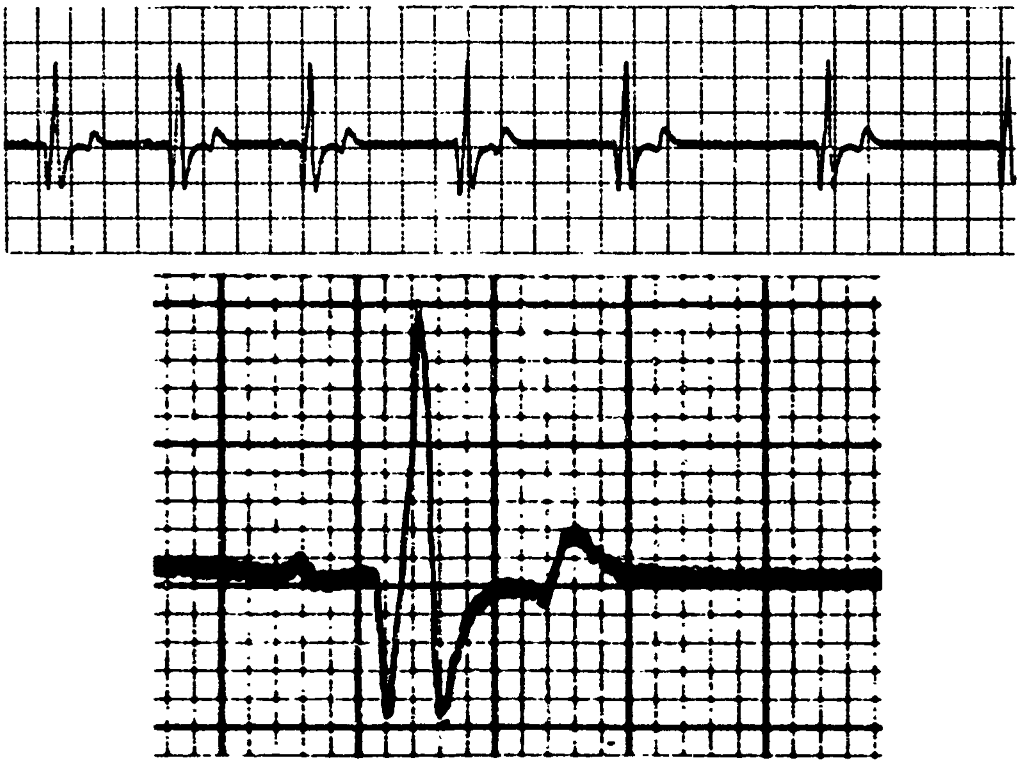

FIG. 6. Heart rate record (electrocardiogram) transmitted by the Iowa Radio-Capsule. The upper line is a record of seven heart-beats. The lower record is an enlargement of one beat, showing that the radio presents the same bioelectrical spikes of each heart-beat as found in records made in a medical clinic.

FIG. 7. Arctic fox carrying radio capsule which provided an EKG record for 9 months.

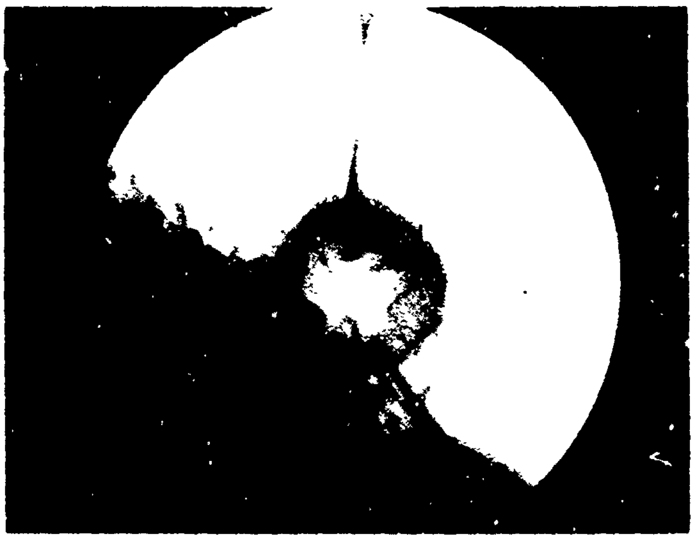

FIG. 8. Photograph of the back of the eye (funduscopic picture) of a red fox captured at Point Barrow. The central disc from which blood vessels radiate is the optic nerve. The pigment mass on the bottom left consists of melanin granules which are considered useful to protect the eye from excessive light.

animal compared with the temperate zone animal; the conspicuous layer which looks like a black tide creeping in to cover the rest of the eye is the pigment layer. The pigment of the foxes in the Midwest appeared to be no different from that of the arctic animals.

Now the question arises as to direction of physiological research: Who will be coming to the Arctic, what will they do, and with what tools will they do it? The present pool of physiologists with arctic experience indicated in Table 2 will and should increase. We must encourage that scientist who is naturally willing to be uncomfortable in the outdoor environment to join those workers who like to obtain data at NARL in the winter. That group of researchers must be ready and willing to live in, to understand, and be unafraid of the rigorous environment of the North. They must be conversant with the problems of airplane accidents on mountaintops or in the Arctic, when the thin wall of protection around man is torn off by the hostile environment that is always ready to bite into his tender skin. If the academic cold-weather physiologists are made welcome, they will

FIG. 9. A photograph obtained by the same technique at the back of the eye of a temperate zone red fox born and maintained in Iowa. In this case the pigment appears to crowd in more closely to the optic disc (optic nerve)

continue to arrive at Barrow winter and summer bristling with enthusiasm and eager for work.

What work will they do? There are new concepts today; the typical academic scientist has been striding energetically forward but has been temporarily stopped in his tracks because of a new demand: he must now not only take time to explain the details of his type of work, his methods, and his objectives but must relate them to the *social* objectives of his area of work. He must now look at his information as a resource: yes, physiological information is a resource. Now that our investigator has his philosophical-motor returned, the emphasis of his research may go in two directions: that of encyclopedic knowledge (pure science), or that of applied science; or the individual scientist may wish to take part in both.

ENCYCLOPEDIC PHYSIOLOGY

The list of physiological topics in Table 2 itemizes the work to be done. Only a small fraction of the information needed on arctic cold weather physiology has been obtained. Part of the reason for this lack is that the "whole animal" research effort in this country as in other countries has been directed towards "molecular biology". This is an important area which has provided a better understanding of matters such as how membrane transport through the intestinal wall is accomplished. The pendulum is now swinging back and there is renewed interest in supporting research which involves the whole animal, especially in relation to his physical environment. The new information must first be organized as encyclopedic or pure knowledge. There are two ways in which this will be used. One is to satisfy the curiosity of alert, well-educated people; the other is to be used by scientists as a stepping stone for further research. The first point was amplified recently by Dr. Van Allen whose name is associated with the radiation belts around the earth. He made the comment that one should not have to justify assembling scientific encyclopedic knowledge as a part of the cultural drive any more than one should have to justify the support of literature, music, or art. Is the American public as a whole interested in encyclopedic knowledge, and does this apply to information concerned with the Arctic Slope? Yes, the eagerness with which semi-popular publications (such as the journal *Scientific American*) "reach-for" information on temperature regulation in the Arctic, indicates a curiosity about the physiological means of survival of animals in extreme environments. Are there more people interested in attending baseball games than there are in attending zoological parks? This is a question which applies to the present paper because at zoological parks today one is apt to find one or several exhibits where the animal is broadcasting its heart rate by radio to the public watching him. The answer is that there were 85 million visits to American zoos in 1968 which is more than the total attendance at all national football and baseball games (Conway 1969). Yes, there is a conspicuous increase in public interest in biological adaptations and thus more interest in the biology of the Arctic Slope than ever before.

APPLIED PHYSIOLOGY

Let us consider the applications of encyclopedic knowledge related to the Arctic Slope and polar area. The instrumented arctic fox in the NARL outdoor cage experiences continuous lack of sunlight in winter and continuous light in summer. Possibly he responds to geomagnetic changes. The scientist who travels to Barrow to study the behaviour of foxes has probably turned *his* biological clock by five hours in one direction or the other. The scientist has a vested interest in finding out whether arctic foxes still have a regular crisp behaviour pattern which remains unchanged in spite of the great changes in solar stimulation. The scientist says: "If the fox can keep his physiological equilibrium and make adjustments in the face of chaotic changes in signals from the environment, so can I." The same scientist may fly from Barrow to Europe where he will now have to change his physiological clock by ten hours. The fox has to adjust to drastic changes in day-night cycles, but man's adjustment may have to be even greater. This has been emphasized by the satellite experiments where primates showed profound physiological upsets due to the accelerated day-night light cycle.

The earlier pictures of the bears symbolize biological studies which help us to understand man's responses when he experiences an accidental reduction in body temperature or a purposeful one for surgery of the heart or the brain. All eyes in this area will be turned in the future to the possibility of finding biological material which will give man a physiological vacation by suppressing his metabolism. Think how helpful such a material would be in time of famine; large groups of human populations could, perhaps, live comfortably on half rations.

In the area of temperature regulation, careful research data have established the temperature characteristics in extreme cold of reindeer, caribou, seals, and of man. Some of these measurements have agricultural applications. Those visionaries who brought 500 domestic reindeer from Norway in 1898 would probably have welcomed some encyclopedic information on the temperature regulation of the caribou before they took their European-type animals across the Arctic Slope. A second agricultural application is the fundamental work of one scientist on the domestic pig; he has explained the mechanism of how these animals as well as seals can tolerate extremely cold weather without a heavy coat of fur.

Now for a medical example: more information about the temperature regulation of arctic mammals will result in the further understanding of frostbite and trench-foot in man. This is of obvious interest to our military services; we are told for example that the cold-weather parachutist may meet a blast equivalent to $-175°$F. ($-115°$C.). Apparently newborn caribou, moose, and seals are rarely affected by frostbite; a great deal more information must be obtained in the next few years on this topic which could be called "comparative physiology of frostbite". At any rate, the animals just listed appear to have extremities which are cold-resistant whereas those of man are not. If this resistance proves to be due to the animals' circulation, then we might be able to increase the resistance of man by the use of drugs which affect circulation.

Some age-old problems still remain. What can we do for the infantryman who must live and work in waist-deep snow? In the future the *reason* he is there may be the failure of his personal jet-propulsion equipment. How shall we get 5,000 to 6,000 food calories into him each day when he exercises (or flounders), how shall we keep the insulation dry for this "tropical man in arctic clothing?"

A final illustration of applied physiology, in this case obtained at NARL, is drawn from the work of W. L. Boyd. He demonstrated and published 18 papers on the remarkable cold resistance in soil organisms which he cultures from the Point Barrow region. If we let our minds soar a bit, we can realize that we might be transporting on our feet or equipment organisms that are very cold-resistant or even insects down to the temperate zone. From the standpoint of practical economics, we depend on Boyd to tell us what might happen if these organisms were released in a climate which might encourage their proliferation.

The final question is: "What tools will the physiologist of the future use?" I have given one illustration of radio-telemetry from arctic mammals; when radio-obtained results are presented, this area of work always seems exciting and attractive. In actual fact the technique is in its infancy (Adams 1969). For instance, battery life is a problem in implanted capsules; it is unusual if a radio in the body cavity of an animal will transmit physiological information for several seasons. Considerable funds and a great deal of time will be required to make this technique more versatile. The usefulness of modern tools in the Arctic was illustrated during the recent journey on the ice pack by David Humphreys and his group. They spent 109 days on the ice and depended on sled dogs for much of their transportation. At one time they travelled to the coast of Greenland for surveying measurements. The sled dogs can be pictured bending low in the harnesses to pull the sleds just as the Eskimo dogs did in the same area 1,000 years ago. Then Humphreys stopped and spent 30 minutes warming up a radio to transmit his surveying readings directly to Minneapolis. There they treated his readings by computer and within minutes radioed back to him a message like this "You have proven that Greenland is 15 miles wider than it has been described before and thus you have added 3,000 square miles to the size of Greenland". I won't vouch for the accuracy of the details of this description, but surely this fascinating combination of the physiology of the sled dog, and the computer in Minneapolis, will symbolize the way that the scientist of the future will obtain much of his information about the challenges which remain to be overcome on the Arctic Slope and the arctic coast of Alaska.

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Progress of Research In Zoology through the Naval Arctic Research Laboratory

LAURENCE IRVING[1]

The first station for arctic research in Barrow was established for two years of observation during the First International Polar Year in 1881-1883. In transmitting his report to General Hazen at the close of the mission, Lieutenant (Signal Corps) P. H. Ray (1885) respectfully suggested that in future expeditions it would be desirable to give the leader time in advance to become acquainted with his crew and their project. In addition to valuable geophysical records, Ray prepared a penetrating description of the ways and culture of the Eskimo people whom he saw before their habits had been much affected by white contact. He made a winter journey of reconnaissance half way to the head of Meade River. Sergeant Murdoch prepared the first comprehensive report on the birds of the arctic coast. Both reports remain interesting reading for their information and literary quality.

At about the same time, Ensign (USN) Howard left Lieut. (USN) Stoney's winter camp on the Kobuk River and, joining a genial company of mountain Eskimos in the Brooks Range, walked with them through Howard Pass to the Colville River. Travelling by boat after break-up he passed from group to group of the sociable inland Eskimos along the route of their annual migration from the mountains to trade on the arctic coast. Howard met Barrow Eskimo people near the mouth of Ikpikpuk River, having made the first traverse by a white man for over 300 miles from the interior of Alaska to the arctic coast. His narrative report (in Stoney 1900) is vivid with his pleasure at the experience in winter and spring arctic travel, and with his appreciation for the kindly and lively friendliness of his Eskimo companions.

Stefansson's (1921) major arctic exploration began with travel along the Alaskan coast east of Barrow where he made anthropological measurements of the inland Eskimos whom he met in their summer visit to the coast near the Colville delta. The survey of mammals, by his associate R. M. Anderson, first clearly brought their arctic Alaskan distribution into view. G. H. Wilkins was a most effective member of Stefansson's party. He returned to Barrow in 1928 to make with Ben Eielson the most magnificent feat of navigation in their flight from Barrow to Svalbard. For this he was knighted. Subsequently, during his busy and venturesome career, his visits at the Naval Arctic Research Laboratory were an inspiration to everyone in the camp.

A. M. Bailey (1948) extended the knowledge of bird life of the arctic coast around Barrow by travel and studies extending over several years. He travelled with and acknowledged the keen help of the Eskimo residents. In his compilation of arctic bird life he credited the eminent Charles Brower and his sons for being first to make known 63 of the then known 153 species of birds recorded from Barrow.

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During the period when Scholander and I were beginning the research at NARL, Professor August Krogh of Copenhagen asked to meet Admiral Lee, who was then Chief of Naval Research. In the course of conversation Professor Krogh alarmed me by asking the Admiral how he could justify value to the Navy in supporting the kind of biological research we were carrying out. I was relieved and still think gratefully of Admiral Lee's answer that "scientific research is as valuable to the Navy as it is good". The scope of research at the laboratory was begun and has continued under those favourable auspices.

Dr. Folk has reviewed (pp. 315-26) the progress of physiological research at NARL in which P. F. Scholander has made such distinguished contributions. I will only add that although there has been illuminating physiological research upon arctic animals there has been scarcely a bare introduction to the probably more interesting physiological processes in the life of arctic plants upon which the whole system of life depends.

In our program of physiological research (1947-49) at NARL we could see many ways in which animals and man are adaptable to the conditions of arctic life. But even now, at the start of a new era of exploitation of arctic resources, arctic conditions are still strange to most of the world's people and are as yet only vaguely understood by scientists from reports of arctic studies. Early in 1947 we realized that information obtained on the arctic coast was detached from the inland country and the world at large because biological studies in the arctic interior of Alaska were lacking. Tom Brower had remarked to me that from reports of inland Eskimos he believed that many birds migrating in spring from southern lands and coasts to the Arctic Slope and coast travelled through passes in the Brooks Range. As we learned later, these passes have long served for communication by men and animals between the forested interior and the northern tundra.

Sig Wien, who was then flying for explorations in the Petroleum Reserve, pointed to Anaktuvuk Pass as the route travelled by arctic-bound aircraft and suggested that the small band of Eskimos (Nunamiut) resident in the mountains could be effective and hospitable guides in studying the connections and communications between the life of the forested interior of Alaska and the Arctic Slope and coast. In November 1947 he introduced Scholander and me to Simon Paneak and the few Nunamiut families then living in skin tents at Chandler Lake. Through these early-established and continued services of the Nunamiut in advising and instructing scientists about their country, scientific descriptions of communications through the interior of arctic Alaska have been established and the science of the coast is no longer detached. This early association has been most usefully maintained and Simon Paneak continues to contribute Nunamiut knowledge as a member of our Institute's staff.

The annual migrations of birds bring large numbers of many species from remote wintering places in North and South America, from Pacific shores and islands and even from continental Asia to nest in arctic Alaska. There are many puzzling factors in these migrations; for instance, a warbler wintering in a circumscribed area of Venezuela migrates to nest in Alaska, with some probability that its winter resort and summer nesting place are faithfully reached within a few miles; the journey is performed with the accuracy of an intercontinental missile. The warbler weighs only 10 grams, yet it contains the entire machinery for aerial nagivation, for memory and operation in flight, and for initiating the journey. Comparison with a missile poses fascinating problems for study.

In 1948 Donald Griffin and Ray Hock surveyed nesting geese along the lower Colville River. By attaching radioactive substances to birds they hoped to trace their habits of homing to nests. Recent developments in radio signalling are now in widespread use and Folk and his colleagues have successfully applied them to monitoring behaviour and rhythmic physiological processes in arctic birds and mammals. Measurements of time, motion and activity are showing most interesting dimensions in the lives of arctic animals.

Sir Hubert Wilkins considered the annual migratory flights of eider ducks past Barrow to be one of the most impressive natural phenomena. With communicating observation points now located along the entire arctic coast there is a chance unparalleled in the world to record by sight and radar the temporal and spatial program of these migrations of birds as well as those of the massive bowhead and white whales and walrus along the arctic coast. News bulletins describing their point to point and day by day progress would be more interesting communications for arctic people than would reports on foreign sports.

Tom Brower and Simon Paneak have assessed the programs of the many birds that migrate through Anaktuvuk Pass, and Simon Paneak, John Krog and I have for 20 years observed the movements and conditions of birds in the Brooks Range to establish physiological characteristics in the process of migration to and from the Arctic. John Campbell has recorded birds in the John River Valley and at Chandler Lake. Latterly with George West and Leonard Peyton we have been defining the annual movements, associations and organization of a population of willow ptarmigan of the Brooks Range and Arctic Slope.

Tom Cade has surveyed the birds along the Colville River and particularly the habits of the numerous peregrine falcons nesting in the cliffs along the Colville. Because birds are visible, identifiable and characterized by seasonal programs in terms of motion and time they have been important in the definition of arctic life and its connection with the rest of the world. Their contribution to studies in ecology and physiology have been outlined by Pitelka (pp. 333-40) and by Folk (pp. 315-26) who, I hope, have not subordinated the view of their own importance in these researches.

Some studies on the arctic fishes have led to comprehensive and still-developing results. Vladimir Walters (1955) made a survey of Alaskan fishes, relating their present distribution to the rapid changes and development of postglacial Alaska. Norman Wilimovsky prepared a key to the fishes of Alaska that, in serving for identification, has widened knowledge of fish distribution and emphasized requirements and rewards from further studies in the very complex aquatic environment of Alaska. Wohlschlag's studies of growth, metabolism and seasonal movements of white fishes in lakes adjacent to Barrow initiated a pattern for a comprehensive view of the life histories of arctic fishes. An interesting sequel has followed in the series of studies by Wohlschlag (1960), and many others, of the metabolic character of fishes living in constantly cold (-1.8°C.) antarctic seas.

A comprehensive study of arctic marine fauna was begun by George MacGinitie (1955) and his wife and continued in collaboration with many colleagues after he served as second scientific director at the Arctic Research Laboratory. This great task is based upon MacGinitie's collections made from a perilously small boat under difficult arctic marine conditions. His skilful selections from his catches have been distributed among collaborating experts whose reports will continue to clarify the previously unknown marine life of the Alaskan arctic coast. The MacGinitie studies show how sustained research brings comprehensive knowledge in contrast to the isolated facts derived in occasional observations.

During the years since 1948 Robert Rausch, with a number of collaborators, has continued pioneering field studies of Alaskan mammals and their parasites. Their reports on systematics, distribution, life histories and relations with Siberia are among the illuminating classics of Alaskan studies in basic zoology and its applications to human health. We have a summary of ecological studies in Alaska by Frank Pitelka (pp. 333-40) in which he has too modestly alluded to the contributions that he and his colleagues have made to basic zoology in arctic Alaska.

J. W. Bee (Bee and Hall 1956) combined the results of his own surveys of mammals with all other records of their distribution in arctic Alaska. Harald Erikson's early measurements of metabolism in arctic ground squirrels preparing for hibernation (Erikson 1956) were followed by his studies comparing the working respiratory exchange of young Eskimo men with young naval personnel stationed at Barrow (Erikson 1957). The volumetric respirometer (invented by P. F. Scholander) employed in these latter studies was subsequently applied to the assessment of respiratory tubercular and other pathological impairment prior to thoracic surgery by Dr. Karl Semb at Oslo, resulting in major improvement in the accuracy of surgical operations and subsequent guidance of recovery.

Keith Miller and I (1962) initiated studies at Barrow on the reaction of hands of Eskimo children to cold showing that children differed from adults; this is now not surprising. These studies are being pursued on Fairbanks school children with increasing neurological refinements by Petajan and Marshall.

My inclusion of people with the other animals scientifically comprised in zoology indicates the importance of studies of Eskimo people furthered by support from the Naval Arctic Research Laboratory. It is out of my competence to discuss the interesting social studies that are basic to understanding how our Eskimo fellow citizens will be fitted into the economy of arctic Alaska that is changing so drastically through exploitation of its petroleum. Rather than emphasize the value of such studies for the indigenous arctic residents I would like to point out that even yet there are very few if any white men who are true residents of the arctic world. Eskimos are naturally adapted to arctic life and we might selfishly examine their ways to see how or even if urban white men can become serious arctic residents instead of transient exploiters.

Significant anthropological studies of Eskimo history were initiated by Ray (1885) at Barrow during the First International Polar Year. Before the Arctic Research Laboratory was established, James Ford (1959) defined by archaeology the stages in Eskimo coastal prehistory at Barrow. With aid and support through NARL, William Irving (1953) and John Campbell (1959) have traced the cultures of people of the Brooks Range far back in antiquity toward the time of the last great continental glaciation. It does not surprise Eskimos that archaeologists have found records showing that their predecessors lived for 8,000 years in ancient camp sites on the arctic coast and tundra. Their instruments, the bones of their food, and associated plants show the circumstances in which the unique Eskimo people and their culture developed. During several millenia they have been a coherent arctic people in arctic lands from Siberia to Greenland over a coastline that Sir John Richardson (1852) remarked is the longest in extent of any used by a single human population.

For several years at Wainwright, Fred Milan has measured physiological efforts involved in Eskimo hunting. An elaborate and diverse program in anthropology is now in preparation as part of the International Biological Program for execution at Wainwright, led by Milan and involving a panel of numerous able anthropologists.

In referring to researches in zoology I have mentioned some that I knew to have been pursued with sufficient continuity to have produced communications that are of lasting influence in arctic science. Deliberately in some cases and inadvertently in others, I have probably omitted names and projects of important consequence. Researches at NARL stimulated the rapid growth of biological research at the University of Alaska, and in the Arctic Health Research Center. This background in arctic biology was the basis for establishing the Institute of Arctic Biology seven years ago and for the development of the Arctic Health Research Center. Exportation of the scientific knowledge obtained in Alaska has been a valuable contribution to the world's culture. Knowledge and understanding acquired in the perspective of views upon arctic life may be the most precious commodity that the arctic contributes.

I hope to have illustrated projects that have opened continuing research about the arctic and that have reflected new understanding about the world at large. I think that a major contribution of NARL is that it has provided means whereby many scientists, be they young or old, could count upon the continuity of their studies through enough years to serve as important parts of their scientific careers. Their arctic studies have greatly advanced the understanding of the participating scientists. Extended arctic studies with good support have converted arctic Alaska from a blank in knowledge to one of the well known regions of the world.

In the present period of rapid social and economic development in arctic Alaska it is fortunate that we have that solid background provided by over twenty years of research at NARL. This knowledge has immense practical value, but it has another value. Scientists in arctic Alaska have expressed the enjoyment and enlightenment derived from their experience in arctic life. The country, its conditions and the way of work and living are intensely interesting. In future years appreciation for the interest and even fascination of participation in arctic life that has been derived in arctic research may become the most valuable contribution from NARL to the newly evolving societies of arctic people. The understanding of that life will help the new residents who enter the country toward the enjoyment that comes from knowledge in the wise exploitation of arctic resources.

ACKNOWLEDGEMENTS

It was a special pleasure and satisfaction for me at the NARL Symposium to be again associated in discussion of arctic research with four of my old contemporaries. I believe that Victor Hessler, George MacGinitie, Dallas Hanna and Ira Wiggins will not mind being referred to as my contemporaries, for I think of them as men whose lives and works have made renewed progress during mature years of devotion to research in arctic Alaska after they had already achieved scientific success in other regions.

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Ecological Studies on the Alaskan Arctic Slope

FRANK A. PITELKA[1]

In the following paragraphs tundra, or terrestrial studies will be emphasized; and in considering tundra the emphasis will be placed on animal studies. But the influence of NARL in expanding ecological knowledge of the Arctic is of course manifest in all realms of the environment, on both physical and biological sides. Ecology in the Alaskan Arctic has moved forward in the last two decades mainly through the leadership of some five agencies: the University of Alaska, the Arctic Health Research Laboratory of the U.S. Public Health Service, the U.S. Geological Survey, the Atomic Energy Commission, and the Naval Arctic Research Laboratory. Among these, the impact on the field of arctic ecology by NARL has certainly been the strongest to date. I do not underestimate the significant roles of the other agencies, least of all that of the University, whose expanding programs of today signal impressively the yet larger role it will play in the arctic tomorrow. But at this time, the prime position of NARL in ecology of the American Arctic is clear. Beginning in 1947, there has been a continuing flow of investigators from various universities, colleges, and government agencies converging onto NARL with the result that the Alaskan Arctic Slope and adjacent waters of the Arctic Basin now comprise one of the best-known sectors of the Arctic, and in many respects *the* best known.

The impact of NARL in ecology of course extends internationally. This is well exemplified for us by the recent publication of Eric Hultén's *Flora of Alaska* with its circumpolar distributional maps. One can only wish that our ties with colleagues in the USSR were not so thin and elusive, so frail and feeble. They have the bear's share of the circumpolar zone of tundra. There is so much about it we should like to know, so much the Russians could tell us and show us, as we want to show and tell them. But speaking only for animal ecology of the tundra, the role of the Russians in this field is nowhere near proportional to their share of the arctic land mass. Being of Slavic origin myself, I may be permitted a bit of Slavic bluntness: The Russian output in ecology of arctic animals does not exploit the ideas in the field as they are at present developing in the West. Most papers we have seen are surprisingly unquantitative and without disciplined problem focus. Their titles are ambitious, but methods are often inadequately described and data are in ompletely or scantily presented. A general review by B. A. Tikhomirov (1959) on animal-vegetation interactions, translated into English in 1966 for international consumption, is heavily descriptive in its content and preoccupied with the elementary fact that plants and animals interact; but it is admirable in its wide sweep of the topic and in the degree to which it raises

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questions and urges teamwork in concentrated study on particular areas. The impressive output of papers in ecology by the Russians' own neighbours — the Poles, the Czechs, and the Finns — provides many models of the sort of information we should like to see from the Eurasian tundra.

There is a new side to the international impact which NARL can have in its support of arctic ecology. I refer to the International Biological Program. This program is dedicated to the study of biological productivity and human welfare. The IBP research programs of the United States are several, but for only two is study in the arctic a specially important consideration. These are the programs on analysis of ecosystems and on human adaptability. Substantial progress has already been made in the study of arctic tundra as an ecosystem, thanks to NARL and to organizations which sponsor research there. This is also true for studies of Eskimos, and indeed an IBP-sponsored study of Wainwright village is already launched. But extent of U.S. commitment to IBP moneywise is, at this writing, still uncertain, and a considerable expansion of research effort in basic ecology of tundra could occur. In this the University of Alaska and scientists depending on NARL would be prime movers. Anyone interested in details of these prospects can refer to my report on an IBP meeting for tundra held at College in October 1968 (Pitelka 1969).

We may first ask ourselves, why should biologists come, or continue to come, to the Arctic to do research? The prime incentives all come from the special features of arctic environment and the special biological conditions which these generate: the low temperatures, the short growing season (or conversely the long winter season), the relatively low numbers of plant and animal species, the distinctive, low-statured vegetation mat, the distinctive make-up of the animal life, and the simple organization of the tundra communities that they comprise. The various questions biologists ask about a particular kind of plant or animal or about a particular kind of tundra habitat all arise from one or more of these environmental features. These questions may be mechanistic, having to do with functional efficiency and adaptation, or they may be descriptive and historical, having to do with distribution and evolution. Who among biologists are attracted to the Arctic? Not just ecologists, but physiologists and behaviorists, less frequently other types of biologists. Working with the biologists are the climatologists, geomorphologists, soil scientists and others who also provide essential knowledge about conditions of existence in the Arctic.

A descriptive base for arctic ecology has of course been provided by explorers and naturalists over the past 200 years. The scientific command of this knowledge grew relatively rapidly, for several reasons: first, the attractiveness of the Arctic, in its remoteness and hostility, to explorers and naturalists; second, the low species diversity; and third, the similarity of the biota through the almost continuous zone of arctic land mass. Fourth, the three factors just mentioned rather soon promoted comparative studies of arctic biotas, which in turn reinforced concern for new information. The result is that our knowledge about distribution of plants and animals of the north is now impressively detailed. But whereas this detail is relatively rich on a large scale, it is usually poor on a small, or tighter local scale, and we have much to learn.

For the ecologists' goal is not merely knowledge of the general conditions of existence, but more particularly, the goal is knowledge of the *consequences of co-existence* among plants and animals. In other words, given the conditions of existence characteristic of the Arctic, we want to know how the plants and animals co-existing in a tundra habitat are functionally interrelated and integrated, what regulatory mechanisms prevail in their populations, and what strategies of exploitation are common or even peculiar to tundra. Co-existing groups of plants and animals in their physical setting of tundra, or further south, display common features of functional organization and are called ecosystems. But in tundra, prevailing responses of plant and animal populations to the extreme environmental conditions mentioned above, make the tundra particularly suited for comparative and analytic work about how ecosystems are organized and how they function. Indeed, tundra is a low-temperature extreme among ecosystem-types on the land areas of the earth and hence it assumes a special importance to the theory of ecosystems; hence, also, the concern about faunistic and floristic work on a tighter, local scale.

I will put this last point more strongly. Future faunistic and floristic work of a general sort, *as an end in itself*, is less and less justifiable in the Arctic; it should rather be done in conjunction with the special needs of ecologists and physiologists whose more focused interests and more problem-oriented approaches raise fundamental questions which often call for the critical help of taxonomists. An excellent example is provided by work under way near Barrow. Here knowledge about decomposition processes is woefully scant (and this is true also for all other ecosystems). On tundra, flies or insects of the order Diptera are especially rich in species and comprise a dominant part of the total insect life. Their larvae are an important but as yet unstudied component in the utilization and breakdown of dead organic matter. Moreover, for some groups of animals, such as sandpipers, they are a primary class of food. Our ignorance of the life cycles of common fly species and their population fluctuations thwart analyses of how these sandpipers depend on a highly varying and rather unpredictable food base (Holmes and Pitelka 1968). Hence the need for detailed studies of the taxonomy and biology of flies of the Barrow area. We need this knowledge of the fly fauna on a local scale broadly for effective analysis of tundra as an ecosystem and particularly for analysis of the conditions that generate the peculiar styles of living we observe among animals in that ecosystem. The excellent Finnish work on chironomids — a key group of flies highly important in tundra economics — exemplifies the sort of intensive study which should be undertaken in the American Arctic (see, for example, Lindeberg 1968, and Syrjämäki 1967, and their earlier papers cited therein).

From these comments on a class of decomposers and a class of predators, we can turn to some aspects of research on tundra as a total system. First, some general points to indicate the magnitude of the job. In Fig. 1 we have a scheme showing the essential components of a life system, be it that of the earth's biosphere or that of just one particular ecosystem. Components and the rates at which energy and nutrients are transferred between them differ between ecosystem-types both qualitatively and quantitatively, and so one thinks of this scheme in realistic

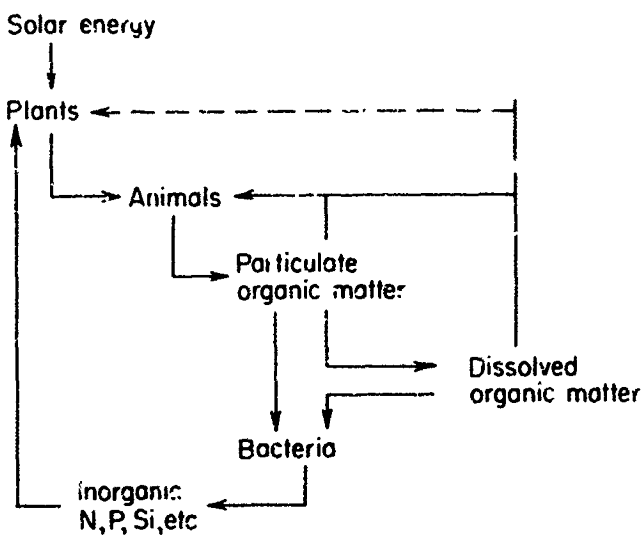

FIG. 1. Energy cycle in the biosphere (from Dunbar, 1968).

terms only for a given ecosystem, a given block of land or water, or a set of such blocks. Furthermore, the scheme shown in Fig. 1 is simplified to barest essentials comprising any ecosystem. A more useful, even if somewhat overwhelming scheme is shown in Fig. 2, where components or compartments (the boxes) and transfer paths (the numbered arrows) give us a more precise breakdown for functional analyses. This is the scheme adopted by the IBP through international conferences for tundra which have taken place in England and Norway. It is planned that studies of tundra in America, Greenland, England, Norway, Sweden, Finland and (hopefully) the USSR will be coordinated so that compatible data will result and so that, minimally, compatible data will be available for certain key components and transfers shown by the heavy-walled boxes and heavy arrows. Clearly, we want and need to know how and to what degree a system such as tundra, which is regionally distinguished by its structural features and its species membership, is also distinctive in its functional properties. The basic pattern of functional organization of ecosystems is the same everywhere, but ecosystems differ significantly, for example, in the proportion of plant matter taken up by herbivores, versus plant matter which dies and is converted by decomposers, versus plant

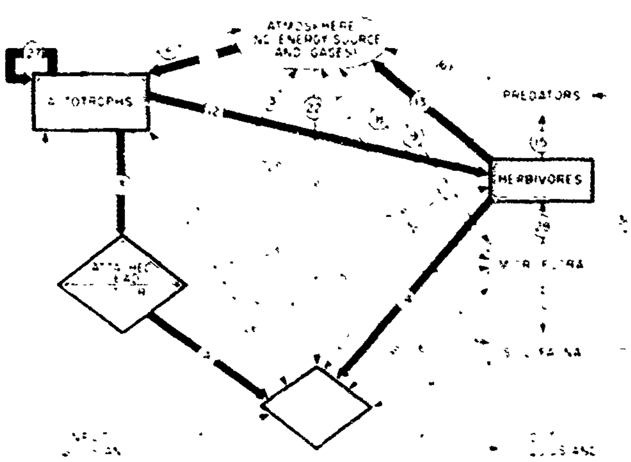

FIG. 2. Flow diagram for energy and nutrients in tundra ecosystems.

matter held in storage as undecomposed organic matter such as peat. The comparison of several tundra sites will provide a test of the generality for tundra of results obtained at any one of them. At the same time, parallel studies in other kinds of ecosystems such as grassland and conifer forest will provide a base for the comparisons we need to discover and assess the special functional properties of tundra.

An entrée into the topic ecosystems as this thinking applies to the Arctic can be obtained from a recent book by Dunbar (1968). He helps to bring out that the last 30 years' research in community and ecosystem ecology have sharpened our grasp of the analytical framework necessary to a proper understanding of productional processes in natural habitats. It has become clear, and IBP has hastened this realization, that for most major advances in the field, organized teamwork of ecologists with physiologists, geomorphologists, soil scientists, climatologists and others is essential. The job before us is enormous, as Fig. 2 shows, but with effective collaboration among researchers and with the use of computers and data-storage procedures, modelling operations and systems analysis, the job should become tractable. A program such as this has already been launched for American grassland with an operational base at Fort Collins, Colorado.

A new urgency for knowledge of tundra as an ecosystem results from sudden developments triggered by the oil discovery in northern Alaska. We know how delicate and unaccommodating tundra is in the face of the gung-ho, hit-and-run style of white man on the economic make; and we know from many small-scale examples how easily and quickly tundra is disturbed and defaced by man. Now we have a Texas-size threat to a land doubtfully able to take it. One recent newspaper headline asked very plainly, "Will Alaska's Oil Start 'Rape of Arctic'?" Our need to deal with ecology of normal tundra has therefore become crucial for now, even more than earlier, we must also deal with ecology of damaged tundra. As Robert Weeden (1969) r cently observed, "Neither science nor government was — or is — prepared for the discovery of oil in the Arctic." This puts the fact of our job to us starkly and bluntly.

Tundra is fascinating to ecologists everywhere for yet another reason: this is the occurrence of strong fluctuations in populations of animals, and particularly the occurrence of cycles in a few plant-eating mammals and birds. For this topic lemmings are legendary, even though a 3 to 4-year cycle occurs among relatives of the lemming at lower latitudes also, down to San Francisco and Jerusalem at least. But this cyclicity is by far most dramatic in the Arctic, and while interest in the mechanism of the cycle continues everywhere, it is especially intense there. It is a fact that for the Arctic, the most concentrated work on the subject has been undertaken near Barrow, thanks again to NARL. The lemming cycle has been monitored since 1949. The fifth cyclic population peak since then is expected to occur this coming summer (1969). The monitoring done by a number of workers has produced a basic picture of cycle characteristics which now provides a basis for a new phase of research. [For background information on the lemming cycle see: Pitelka (1957); Krebs (1964), and Mullen (1968).] Particularly timely would be intensive work on the metabolic physiology and feeding ecology of lemmings related to the cyclic phase

Ecology of the vegetation base which supports this cycle also needs continuing study. That plant production of grass-sedge tundra in the Barrow area is temperature limited (as has been stated for tundra elsewhere) was shown by A. M. Schultz (unpublished manuscript) in experiments at NARL in which blocks of vegetation and sod brought into a greenhouse and maintained at 20-25°C. produced 3 to 4 times as much dry biomass as similar vegetation growing under field temperatures. But natural vegetation experimentally fertilized in the field produced 4 times as much dry biomass as that left unfertilized, and its nitrogen and phosphorus content per unit weight was twice that of controls so that there was an 8-fold increase in yield of N and P on the treated plot. Thus, astride the temperature effect is a more fundamental limitation, that of nutrient supply. Here we need a great deal more quantitative observation and measurement along with experimentation, not just in relation to lemmings but in relation to all parts of the food web depending on the plant base.

I want lastly to bring out a general point about the tactics some arctic animals use in coping with the marginal existence offered by tundra — tactics whose understanding adds to ecosystem theory. Let me say parenthetically that I do not subscribe to the notion that evolution of species richness in the Arctic is still catching up because of the recency of glacier recession. I do not think that evolution is proceeding any more rapidly in the Arctic than elsewhere. Capacity of animals to disperse is strong in spite of their differing equipments. The relative success of population pressures by animals of all kinds through time to use tundra resources is shown by the fact that the fauna of, for example, flies exceeds 100 species for a given arctic area whereas the number of species of beetles may be just 5 or 6.

For highly mobile animals such as birds, there is a wide range of tactics, or strategies, in life-style among arctic species, even among those co-existing on the same acreage of tundra. By "life-style" I refer to what more technically is

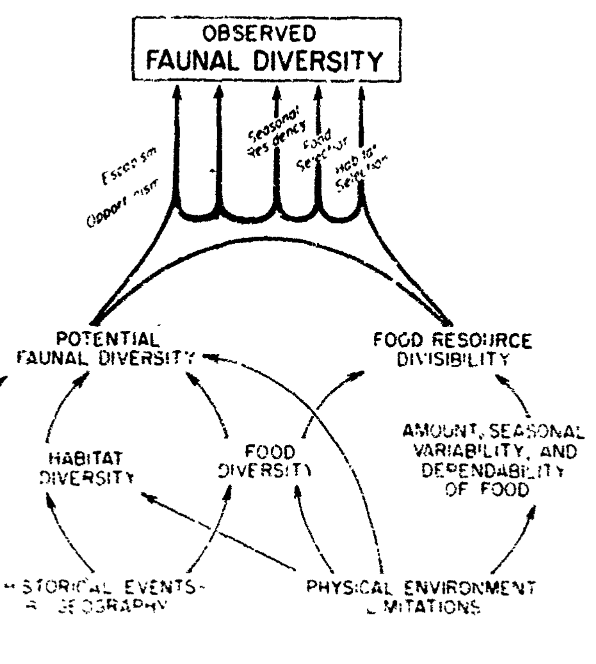

FIG. 3. Factors (boxes) and strategies (arrows) influencing observed faunal diversity within an ecosystem-type such as tundra.

often termed "social system"; that is, the adaptive pattern of deployment of the individuals of a population through time and space, especially with regard to production and survival of young. Variety in social systems among co-existing species is an evolutionary tactic serving to "push" the capacity of a habitat to support more species. Tundra and its bird life provide an excellent example.

Fig. 3 illustrates a base of thinking about richness or diversity of species in a given ecosystem (we are concerned about diversity of animal species, hence "faunal" diversity). The foundations of this matter packaged in the lower part of the figure are, for the most part, general knowledge of modern ecology and biogeography. Our concern now is with the arrows representing resultants for tundra from the mesh of factors determining species diversity anywhere. First, as elsewhere, species of birds separate into different habitats, and within each habitat, they separate according to type of food used. In tundra, seasonal change is strong, and the species diversity is greatly augmented by migrants coming North to breed. But among these, the commitment to breeding does not include necessarily a regular cost, so to speak, paid by tundra resources. Migrants do not all stay 2½ to 3 months, nor are they on a given acreage of tundra every year. Some species practice "opportunism," breeding in numbers beside more conservative, regularly present kinds of birds when food is abundant. These are "prosperity" opportunists. There can also be "depression" opportunists, exploiting some foods too scarce for specialists but sufficient if combined. An especially significant strategy is "escapism" (MacLean and Pitelka unpublished manuscript). Various species, notably among ducks and sandpipers, come to the Arctic to get the breeding effort going, but then one parent departs quickly, followed by the other as soon as possible, so that the growth of young is risked minimally by the energy needs of parents. Various aspects of this topic are developed in more detail in manuscripts being prepared for publication elsewhere. The timing and spacing features of the bird populations are the better known parts of this picture; the food relationships are the difficult, more speculative parts. The fact of a variety of tactics remains, and this variety is evidently so wide among tundra birds because of the highly fluctuating character of the environment and, therefore, the highly variable food supply.

It is because of the occurrence of these distinctive strategies at times even among closely related species such as sandpipers (Holmes and Pitelka 1968) that the tundra is a significant source of insight into how species diversity can build up and thus how the membership of an ecosystem can build up. While this aspect of ecology stresses knowledge of particular groups or organisms such as birds, their population dynamics, physiology, and behaviour, it is absolutely basic, as I think we can see, to the furtherance of the theory of ecosystem structure and function.

Here, then, are several aspects of ecology which are central in the field as a whole and whose study in the Arctic is especially promising and even critical. None of this can occur without facilities and support of the sort NARL has provided. In its new home, it will be yet more effective in the growth of ecology and of arctic science generally.

ACKNOWLEDGEMENTS

I should like to acknowledge my heavy professional and personal indebtedness to the Naval Arctic Research Laboratory and to all persons and agencies that have made and continue to make NARL possible.

My work at Barrow began in 1951, after a brief but warm invitation to apply for support sent to me in October 1950, by Ira L. Wiggins, who was then beginning a term as the scientific director of NARL. Ira Wiggins' kind gesture was the trigger for a long series of new research associations and friendships with fellow scientists and students, here and abroad. The Arctic has been our common bond, and the tundra, in reality or in theory, has been a target we have shared in continuing inquiry. For all this, my humble thanks and boundless gratitude to NARL.

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Arctic Plants, Ecosystems and Strategies

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The expansion of both the rate and the impact of man's well-oiled technology have made his concern and understanding of the entire biosphere relevant, and indeed essential. The amount of critical knowledge about himself as well as his environment and resource base has, unfortunately, not been his prime concern nor is the amount of information required to operate "spaceship earth" readily attainable. We do not now know the minimum number of kinds of organisms required for man's survival and for the orderly regeneration, regulation and self-cleansing necessary to perpetuate any ecosystem. There are many ample examples of misbehaving systems with unstable epidemic populations, declining productivity, and polluted or toxic environments.

What do we know and what do we need to know about the structure, function, and adaptive strategy of arctic tundra ecosystems? By ecosystem I refer to a unit of landscape, an ecological system composed of associated plants, animals, microbes and their environment. Such systems are open not closed, they are dynamic not static, the biota co-exist and interact with their environment and with each other. The organisms have evolved various adaptions and the ecosystem has developed complex interdependencies in order to survive. In developing a perspective rather than a review, I shall concentrate on plants, the primary biological producers of any ecosystem.

ARRAYS IN TIME

Plants and vegetation mixtures are arrayed in both time and space. Their evolution and migration over geologic time scales contribute to their present spatial distribution.

Succession

Shorter-term change in plant arrays, particularly following disturbance of the natural assemblage, is due to ecological succession. Succession is one of the more important concepts for ecosystem management and manipulation in temperate latitudes, but the phenomenon is poorly understood for tundra ecosystems (Churchill and Hanson 1958). Fragmentary evidence is accumulating that succession does occur as new habitats are colonized (Bliss and Cantlon 1957; Britton 1957; Viereck 1966) or in response to freeze-thaw activity in tundra terrain (Benninghoff 1952; Hopkins and Sigafoos 1951; Sigafoos 1952; Johnson and Billings 1962; Troll 1958). We know little about the rates of vegetative recovery

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or succession in various types of tundra. There are observations at Barrow that suggest reinvasion of some upland vehicle trails within five years. There are other examples of irreversible destruction of tundra in which albedo is lowered from an average of 20 per cent to 10 per cent or lower and the heat coefficient is altered so that thermokarst processes are activated and shallow ponds replace meadows.

Redistribution and Migration

Modern vegetation assemblages began with topographic changes imposed by uplift and the resulting climatic shifts during the late Tertiary and Pleistocene. These vegetation patterns continued to shift and differentiate in response to repeated glaciation. Two major sources of floral migration are especially significant to Alaska, the Bering Land Bridge and unglaciated refugia. There is increasing evidence that major elements of today's biota including man crossed the broad land bridge that spanned Bering Strait during the Wisconsin glacial period until about 11,000 B.P. (Péwé *et al.* 1965).

Reconstruction (Heusser 1965) of late- and post-glacial pollen spectra (Fig. 1) from the efforts of several investigators indicates that forested areas in Alaska contained about the same species as at present. Composition of arctic tundra

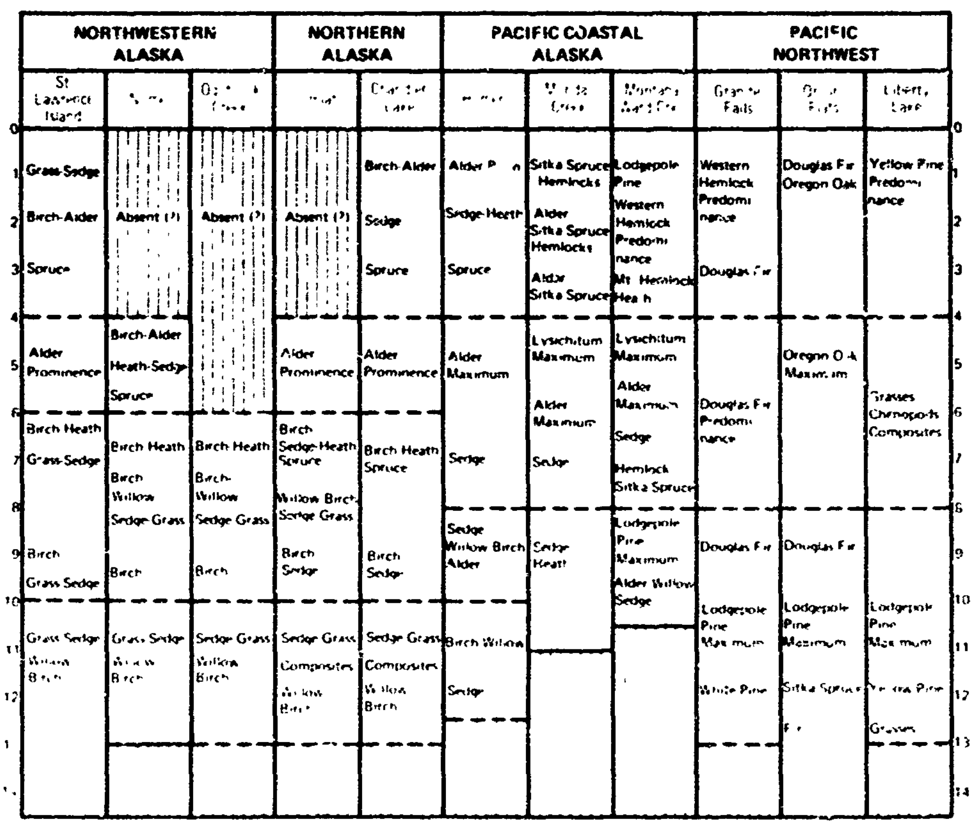

FIG. 1. Summary of late-glacial and postglacial vegetation for selected sections summarized by Heusser (1965). Vertical lines appearing at the bases of most columns cover intervals for which no record is available. Where they terminate above by a solid cross-line, the pollen-bearing sediments are radiocarbon dated; dash cross-lines indicate age inference from regional dating. The upper portions of the sections from Nome, Ogoturuk Creek, and Umiat appear to be truncated (from Heusser 1966).

evidently shifted from dominance by sedges, grasses and composites to birch shrubs that were subsequently invaded by alder at the thermal maximum.

Steere (1965) points out that of 500 bryophyte species known from the circumpolar Arctic, over 60 are considered restricted to the high Arctic, although far less endemism can be substantiated than formerly thought. The intriguing patterns of disjunct distribution of moss species suggest many close relationships with tropical rather than temperate flora. In combination with the known unglaciated habitats that persisted throughout the glacial epoch, these disjunct relationships suggest that many arctic mosses have remained essentially unchanged since Tertiary time.

The distribution and migrations of tundra flora continue to be objects of insight into Pleistocene events as well as evolutionary strategies. One clue is the frequency of polyploidy. These generalizations about multiple chromosome complements have emerged:

1) Arctic plants have substituted asexual for sexual reproduction particularly among perennial herbs under environmental stress; thus, polyploidy may not be limiting to perpetuation of the genotype.

2) The availability of new ecological niches, as following deglaciation or gross climatic change, favours establishment of polyploid species.

3) Polyploidy is generally thought to be a percentage of the flora inversely related to latitude in the northern hemisphere (Löve and Löve 1957).

4) Polyploids are considered more successful in extreme environments than their diploid relatives. Thus, arctic diploid species are interpreted as ancient arctic-alpine genotypes occupying drier or more stable habitats including snowbed communities (Johnson *et al.* 1965). Polyploid species have spread out over the Arctic during post-glacial times and occupy sites with greater cryoturbation.

Johnson and Packer (1965) demonstrated for the Cape Thompson, Alaska, flora a correlation of polyploidy with an edaphic gradient. The polyploid frequency was lowest in warmer, drier, more stable habitats and increased with greater soil disturbance. Clearly, a regional percentage represents an integrated flora existing over the range of habitats available. The fact that polyploids are more successful than diploids in disturbed periglacial habitats prevalent during glacial periods, combined with the unglaciated condition of interior and northwestern Alaska in contrast to glaciated northern Europe, is of major significance in accounting for the lower frequency in European floras (Johnson and Packer 1965, Packer 1969).

The relationship of polyploid success to extreme environments is further supported by Packer's (1969) studies of the Canadian Arctic Archipelago. The frequency of polyploidy on 15 islands provides no evidence of a gradient correlated with latitude. Rather the observed distribution is more nearly associated with summer isotherms. That is, temperatures ameliorate toward the NE, SE and SW from Prince of Wales Island and polyploid frequency among dicots tends to decline accordingly from close to 70 to 50 per cent on Southampton Island.

ARRAYS IN SPACE

Vegetation Assemblages

The arctic flora is now reasonably well known except for fungi. We are indeed fortunate to have the excellent flowering plant manuals of Hultén (1968) and Wiggins and Thomas (1962). Hultén includes 1,559 species of vascular plants in 89 families and 412 genera for the Alaska region. Spetzman (1959) lists 439 taxa in 53 families for the coastal plain, foothill and mountain provinces of the Alaskan north slope. There appear to be approximately 100 vascular species at Barrow, 250 species at Umiat (Britton 1957) and 300 species at Cape Thompson (Johnson *et al.* 1966). Of 220 species at Meade River, at least 84 are also found at Barrow and about 170 are common to Cape Thompson. The reduction in species diversity northward is more likely related to a reduction of ecological niches related to topographic and habitat diversity rather than simply intensification of climatic parameters.

Krog (1968) has recently provided an account of 348 species of macrolichens for Alaska. This compares with 375 species for Fennoscandia, although the list is certainly incomplete for Alaska. From existing records of lichen distribution Krog concludes the following composition:

	Per cent
Circumpolar species	61
Disjunct species occurring in Eurasia and North America	14
Asiatic-North American species	15
North American west coast species	7
North American species with affinities in Southern Hemisphere	3

Descriptive accounts of vegetation of the Alaskan Arctic by Spetzman (1959), Johnson *et al.* (1966), Benninghoff (1952), Bliss (1956), Drury (1956), Hanson (1953), Hopkins and Sigafoos (1951), and Wiggins (1951) are particularly helpful. The classic, however, on arctic vegetation on the northern slope of Alaska continues to be Britton's (1957) eloquent description. Most of his observations and insights continue to be further documented and substantiated (i.e. Cantlon 1961; Clebsch and Shanks 1968; Pitelka and Schultz 1965). An elaboration (Table 1) of habitats and communities appropriate to coastal plain tundra with distinctive indicator species was developed from field studies at Meade River.

What emerges from the descriptions of arctic tundra is the impossibility of understanding tundra dynamics or even vegetation associations without a parallel examination of topographic microrelief, soils and thaw depths that collectively constitute the substrate for plant life. Accepting the three physiographic units generally recognized for the north slope, mountains, foothills and coastal plain, Cantlon (1958) proposed that within major regions three scales of topographic relief were important: macro-, meso-, and microrelief. Although he did not propose measurement units, these three scales are approximately on the order of hundreds to tens of metres, metres, and centimetres of vertical relief respectively. Such a concept is supported by the development of different soil types along topographic gradients that primarily reflect drainage and snow cover gradients (Brown 1966,

TABLE 1. Physiographic habitats and ecological communities of Arctic Coastal Plain tundra in Alaska

Physiographic Habitat	Community Type
River Bars	1. Open pioneer communities 2. Riparian willow 3. River bar tundra
River Cutbanks	4. Bluff (a) Turfy (b) Sandy 5. Wet slump slope 6. Dry slump slope 7. Snowbed gullies
Sand Dunes	8. Active dunes 9. Semi-stabilized dunes 10. Stabilized dunes
Streamside	11. Stream margin 12. Streambank 13. Floodplain
Lakes and Ponds	14. Open water 15. Emergent grass 16. Aquatic sedges 17. Wet sedge bog 18. String bog 19. Sphagnum hummocks 20. Pond margins
Low Centre Polygons and Ridges	21. Wet tundra 22. Wet sandy flats 23. Tussock tundra
Polygon Troughs	24. Muddy troughs 25. Peaty troughs 26. Wet mossy troughs 27. Sedge troughs
Upland Tundra and Ridges	28. Lichen barrens 29. High centre polygons 30. Snowbed
Disturbed Sites, Dry	31. Recently drained lake sediments 32. Squirrel burrows 33. Abandoned dwelling sites (a) Moist (b) Dry 34. Airstrip and mine tailings
Disturbed Sites, Wet	35. Drainage ditches 36. Excavation ponds 37. Caribou, other carcasses 38. Vehicle trails

Tedrow and Cantlon 1958). Studies at Cape Thompson by Johnson *et al.* (1966) showed the relations of the principal plant communities to relief, soil type and permafrost (Fig. 2).

Attempts statistically to correlate vegetation type with parameters of the atmosphere or lithosphere in local areas generally produce positive correlations with thaw depth and soil moisture, but inconsistent results with other variables. Recent studies have attempted to examine complex relationships (Brown and Johnson 1965, 1966) but simple relationships do not yet exist. The accumulating information on arctic pedology and cryopedology (Brown 1965, 1966, 1967, 1969; Douglas and Tedrow 1961; Drew and Tedrow 1957; Hill and Tedrow 1961; Tedrow *et al.* 1958) is encouraging. An integrated view of plant-soil interactions may soon solidify, thanks particularly to the efforts of Tedrow and his associates.

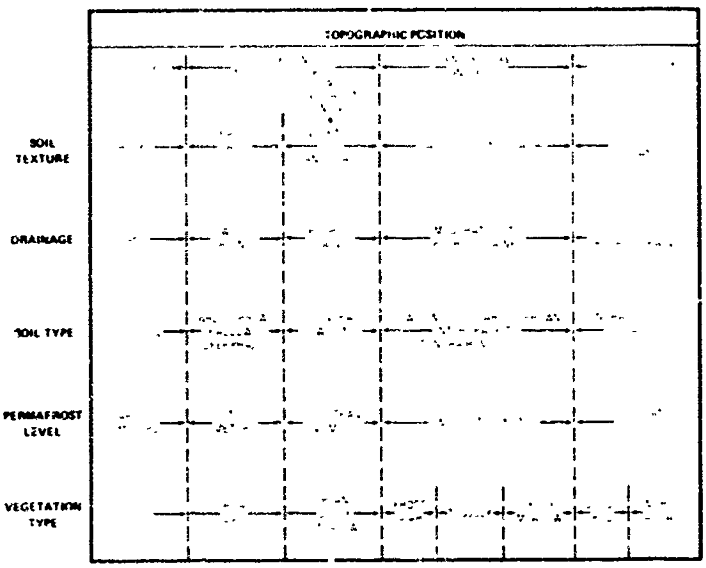

FIG. 2. Relationships between soil characteristics and vegetation along topographic gradients in the Ogoturuk Creek valley, Alaska (from Johnson *et al.* 1966).

In the interim the following major soil groups are recognized: Lithosol, Podzol-like, Upland Tundra, Arctic Brown, Meadow Tundra, Half Bog, and Bog (Tedrow and Cantlon 1958, Tedrow and Brown 1968). There is also evidence for an arctic Rendzina and a shungite soil (Ugolini *et al.* 1963).

STRUCTURE AND FUNCTION

The vegetation of arctic ecosystems is comparatively simple in both composition and structure, although far more complex than is suggested to the uninitiated observer. Herbaceous perennials and low shrubs are the most abundant life form, annuals are rare or absent. Common morphological adaptations include: 1) Cushion or polster life form, 2) rosette life form, 3) leafy stemmed plants, 4) graminoid including tussock formation, and 5) prostrate, diminutive woody shrubs. Clearly these forms are a response (Bliss 1962a; Tikhomirov 1963) to climatic moderation close to the ground, even beneath seasonal snow. Tussock formation may also be advantageous for maximum solar interception at low sun angles characteristic of high latitudes.

Carbohydrate Cycle

Growth is rapid immediately following snow melt (Billings and Bliss 1959; Warren-Wilson 1960, 1966; Wager 1938). This is apparently possible because of the large amounts of carbohydrates and starch stored in roots, rhizomes and corms (Mooney and Billings 1960; Russell 1940b). It appears that the ratio of live standing above ground to live below ground biomass is about 1:5. Metabolism occurs at low growing season temperatures, near 0°C. The short growing season of some 70 to 80 days requires that the yearly vital events be consummated in a short period (Fig. 3). Thus, food storage underground in herbaceous plants as carbohydrates or as lipids (Bliss 1962c) in old leaves of evergreen shrubs is characteristic of arctic and alpine plants. Asexual reproduction including apomixis

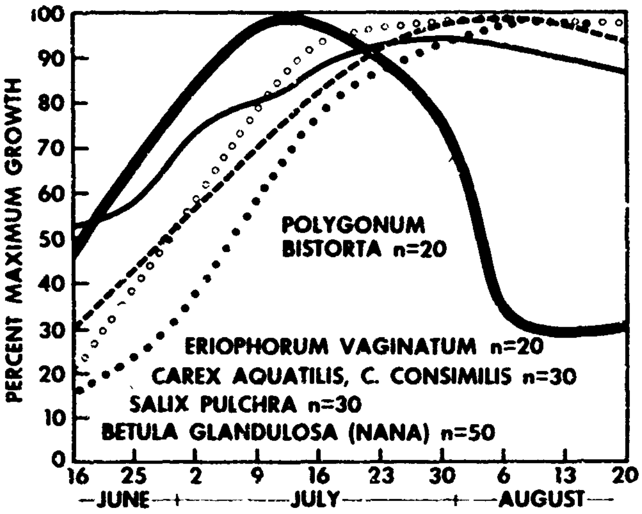

FIG. 3. Growth of 150 plants as evidenced by stem and leaf elongation as a percentage of maximum length at Meade River, Alaska, in 1966. By the third week of July, 90 percent of vegetative growth had occurred. The growth curve for *Polygonum* clearly indicates a period of growth followed by a flowering period, and then carbohydrate translocation to a thick rhizome as the leaves shrivelled.

and vivipary replaces sexual reproduction as a response to a shortened growing season or unfavourable climatic condition. We know comparatively little, however, about events that condition flowering or seed set in any given year. We do know that flower buds are usually pre-formed the previous growing season, but complete development and anthesis depends on temperature of the flowering year and some species may have a photoperiod requirement (Hodgson 1966). Seed dormancy is environmentally controlled, but seeds can remain viable for long periods of time at low temperature, since they require temperatures well above freezing for germination (Bliss 1958, Amen 1966). Optimum germination temperatures seem to be 20 to 30°C., but seedling establishment commonly requires several years. Thus sexual reproduction is opportunistic and vegetative propagation is more reliable.

Chlorophyll Content

The distribution of chlorophyll in plant communities is one common parameter of diverse species and morphologies. Examination of chlorophyll per unit area at Meade River, Alaska (Tieszen and Johnson 1968) showed that mosses in dry sedge stands might contain over a third of this vital pigment, whereas in wet sedge stands chlorophyll was nearly all contained in *Carex aquatilis*. The amount of pigment in different communities including dry and wet sedge tundra, low shrub willow, and cotton grass tussock tundra (0.32 to 0.77 g.m.$^{-2}$) was highly correlated with the production of plant biomass. However, chlorophyll concentrations varied among different communities from 1.5 mg.g.$^{-1}$ in dry sedge tundra to 8.8 mg.g.$^{-1}$ in wet sedge tundra on a dry weight basis. One suspects the opposite relationship for cellulose and other supporting tissues.

On a land area basis chlorophyll content is about the same in alpine (Bliss 1966) and arctic tundras as well as being similar to temperate herbaceous communities (Bray 1960). Within the same species there is more chlorophyll in leaves of arctic populations than for alpine populations (Billings and Mooney 1968). Mooney and Johnson (1965) using *Thalictrum alpinum* in growth chambers found that the 25 per cent higher pigment content in arctic populations was genetically controlled.

Associated with adjustment in pigment content are wider but thinner leaves in certain arctic versus alpine plants (Tieszen and Bonde 1967). Billings and Mooney (1968) concluded that green pigment content was both genetically and environmentally conditioned. The lesser values for alpine populations are in clear contrast to arctic plants and also in contrast to lower elevation plants. Ultraviolet radiation is in part responsible for rapid breakdown of chloroplasts, but some species of plants may have too slow a rate of protochlorophyllide synthesis to keep ahead of photo-oxidation in bright light at low temperatures.

Physiological Ecology of Plant Populations

The experimental approach to processes in arctic and alpine plants and ecotypes of the same species has yielded an important insight into adaptation to severe environments at the species population level. From recent reviews of work by Bliss (1962b) and Billings and Mooney (1968) and their students the following conclusions seem justified:

1) Metabolism of the phenotypic plant is controlled by both genetic variation and by past and present environments. The actual diurnal and seasonal courses of photosynthesis and respiration are the result of complex interactions between genetic plasticity and environmental control.

2) Plants of arctic populations have a higher photosynthetic rate at lower temperatures and attain a maximum rate at lower temperatures than do alpine plants.

3) Arctic plants have higher respiration rates at all temperatures than do alpine plants.

4) Light saturation for arctic plants is reached at lower light intensity than in alpine plants. In *Oxyria digyna* populations grown in growth chambers at 20°C., for example, northern populations (61° 23'N.), were shown to be saturated at 2,000 f.c., whereas southern latitude (39° 40'N.) high elevation plants were not saturated at 5,200 f.c.

5) There is a clinal increase in the photoperiodic requirements for flowering from southern to northern populations.

6) Arctic plants are much less tolerant of high temperatures than alpine plants. In demonstrating biochemical differences in the photosynthetic mechanism of the Hill reaction in *Deschampsia caespitosa*, Tieszen and Helgager (1968) support the same conclusions.

Thus there is strong evidence from different populations that suggests evolutionary adaptation to the specific light climate by adjustment in growth and flowering response, perennating bud formation and photosynthetic. respiration balance. The close relationship between tissue temperature and rates of photosynthesis and respiration strongly suggest that maximum daytime temperatures is the critical environmental factor distinguishing arctic and alpine gene pools from subarctic or subalpine populations (Billings and Mooney 1968). Although annual productivity is low, daily rates of carbon fixation during the peak of the growing season can be as high as most temperate herbaceous vegetation (Billings and Mooney 1968), ranging from 0.5 to 5.0 g.m.$^{-2}$ day^{-1} for shoots and perhaps up to 11 g.m.$^{-2}$ day^{-1} if root productivity is included.

Tundra Ecosystems

Holistic approaches to arctic ecosystems have been reported only recently. Gore and Olson (1967) attempted one of the first applications of systems models to account for the accumulation of organic matter in a British *Eriophorum-Calluna* bog. Johnson and Kelley (1969) have presented a carbon budget (Table 2) for an arctic coastal tundra ecosystem based on measurements of biomass and carbon dioxide flux (Table 3).

TABLE 2. Dry matter production in an arctic tundra ecosystem for a growing season[1]

	$g.m^{-2}$	*Source of Data*
Gross Top Production, GTP	109	Chamber Measurements
Net Top Production, NTP	82	Harvested Plots
Net Root Production, NRP	100	Dennis 1968
Estimated Net Production, NP	182	NTP + NRP
Top Respiration, TR	27	GTP—NTP
Root Respiration, RR	135	Douglas and Tedrow 1959
Primary Respiration, R	162	TR + RR
Gross Primary Production, GP	344	NP + R
Litter, L	273	Harvested Plots

[1]From: Johnson and Kelley 1969

TABLE 3. Annual carbon flux in arctic tundra

Atmosphere 3770 g. CO_2 M^{-2}

		↓ 10.8%		5.6%	↑ 5.3%
		Gross Photosynthesis		Net Storage	Summer Respiration
Vegetation	Tops	109	=	82	27
	Roots, Rhizome	235	=	100	135
	Primary Production	344	=	182	162

Sufficient data have been accumulated by a spectrum of investigators at several tundra sites to justify pooling and synthesizing the available data before much further field investigation is undertaken. Primary productivity (Bliss 1962a) in tundra ponds at Barrow was determined by Kalff (1967a) to be only 380 to 850 mg.m.$^{-2}$ year^{-1}, but to be 8.5 g.m.$^{-2}$ year^{-1} for Imikpuk, a freshwater lake (Kalff 1967b). Hobbie (1964) reports 6.6 to 7.5 g.m.$^{-2}$ year^{-1} in oligotrophic Lake Schrader and even less for Peters Lake. Thus freshwater productivity is relatively low primarily because of a short growing season and perhaps because of low nutrient availability.

Pieper studied above ground biomass and chemical composition of *Dupontia* meadows, and Dennis has measured standing crops of above as well as below ground vegetation in several communities at Barrow. At Barrow net shoot production varies from 3 to 97 g.m.$^{-2}$ year^{-1} depending on the site and grazing intensity. Various nutrient cycling studies are reported by Barsdate (1966), Brown *et al.*

(1968), Kalff (1968), Likens and Johnson (1968), Pitelka and Schultz (1965), and Russell (1940a). While considerable data are now available on concentrations of the more important minerals little is known about their rates of uptake, retention and release.

Much is known about the more important animals at higher trophic levels in the food web (Holmes 1966; Holmes and Pitelka 1968; Bohnsack 1968; Mayer 1954; Mullen 1968; Pitelka 1957, 1959; Pitelka *et al.* 1955; Thompson 1955; Weber 1950). Considerable macro- and microclimatic data are available from Barrow and certain other arctic sites. Thus we can begin to construct a general ecosystem model for tundra with appropriate compartments and pathways for transfer of energy and materials. Mathematical equations can then be written to express the rate functions of such a network in order to achieve a predictive model.

A model is only a concept, a vehicle for stating a complex hypothesis, its validity and applicability must be tested. That, in fact, is the intent of the tundra project in the International Biological Program. From the beginnings made in other biomes, and by the tundra project, it is possible to foresee a variety of models. Regional models will express the differences between major tundra types such as British blanket bog or a Finnish lichen-reindeer system. Other models will express in greater detail an individual process such as the functioning of the photosynthetic apparatus. To the degree that predictive ability is generated by these models, a powerful tool for landscape management will be created. We have learned elsewhere that new insight into the complexities of whole ecosystems is gained through stressing the system by some manipulation. Often these stresses are created inadvertently, but it seems very likely that future field strategy will be less observational and more experimental.

From the Arctic, the ecologist is learning the many facets of a complex natural system, how and where it originated, how it develops, how it survives. It is a great natural system in which the first Americans also arrived, evolved and survived. By examining the anatomy and metabolism of tundra, which is simpler in diversity, architecture, and number of interactions than those at lower latitude, we strive to learn principles applicable to those more complex systems. Do the conclusions suggested from experience elsewhere fit the Arctic? Usually not without modification. The unique stresses of the arctic environment from day length to permafrost afford additional dimensions to learn tolerances and limitations of organisms. Furthermore, as man and his technology add new stresses to an already fragile system we can learn about processes at work by the response of these individuals, populations and ecosystems

STRATEGY FOR LIVING

With what strategy should society view the Arctic? The wealth of the Arctic does not glitter; yet Robert Service associated it with exploration. Tundra has long been one of those few remaining areas in this world which man could ponder or disregard at his leisure. Are we about to witness the exploitation of the Arctic? Robert Weeden (1969) thinks so, as he explained in a recent address on Arctic Oil. So do those concerned with the economy of Alaska, but from different motivations. As Garrett Hardin (1968) expressed it, in a thought-provoking article, "The tragedy of the commons" is upon us. By the "commons" he meant that village pasture available for the use of all citizens. This right of mutual ownership was stressed by too many citizens with too many grazing cows, and so we have abandoned the commons for food gathering. We fence and post land, we place restrictions on an increasing number of human activities from hunting, waste disposal, parking, and building, to mining. We are trying to cope with regulations for pesticide applications, noise abatement, and radioactive contamination. Each new enclosure of the commons infringes on somebody's freedom. How much longer can we preserve the freedom to breed, for it will soon beget misery. As both Hardin (1968) and Allen (1969) emphasized again recently, the human population problem has no technological solution. What strategy can we soon invoke to assure adequate food, space and sanity among men? Allen (1969) correctly observes, "The wild creatures of this earth have survived because each performs a useful function in a reasonably stable ecosystem. Any living thing that is too successful destroys the sources of its livelihood and disappears with the community on which it depends. Man's vast power play in using, if not inhabiting, nearly every environment on this planet could be self-defeating if he does not have the insight to impose his own controls and work for that necessary stability in his ecosystem."

The value systems developed in our society have a Judeo-Christian basis, our science is distinctly western. Its dominant attitude is egocentric about man and exploitive about nature. Is not this what we mean when we speak of *developed* country? In a provocative article on "The historical roots of our ecological crisis," White (1967) concludes that, "Despite Darwin, we are not, in our hearts, part of the natural process. We are superior to nature, contemptuous of it, willing to use it for our slightest whim. . . . Hence we shall continue to have a worsening ecologic crisis until we reject the Christian axiom that nature has no reason for existence save to serve man."

How then can we view the world and arrive at appropriate strategies? Certainly not by extending the doctrine of prior appropriation, a legal concept that developed in relation to water resources. A point of view that integrates ecological and socioeconomic systems is essential. Man's physical, physiological and psychological requirements will be fulfilled only if ecological, economic, engineering, educational and ethical thoughts are combined. The thoughtful reader will, I hope, recognize that I refer to a philosophy that runs far deeper than the virtuous conservation ethic.

Fortunately, there is increasing awareness among the public, an anxious involvement among professionals and some frantic rhetoric from a few of our public administrators. The noise is not too great to listen or learn. Technology assessment, environmental monitoring, and regional planning are necessities. But one of the soundest bases for coping with our environment and its resources is probably the development of ecosystem zoning (Odum 1969) as a rational means of resource and space allocation; this we have already begun to do in urban ecosystems. We have sufficient information to plan some ecosystems wisely for certain activities. Clearly the nation needs a greatly expanded ability to acquire ecological information in a coherent, integrated and purposeful manner. Multidisciplinary research programs organized in response to the International Biological Program could very well forecast in a small way the beginnings of a new, more rational and more beneficial strategy for living.

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The Growth of the Naval Arctic Research Laboratory

ROBERT A. FROSCH[1]

"It is my pleasure to speak at the closing session of this symposium which has done so much to illuminate past achievements of the Navy and national research programs at the Naval Arctic Research Laboratory. The meetings have been stimulating and informative, the hospitality outstanding and my entire experience in Fairbanks and College most interesting.

"This is my second visit to Fairbanks, and tomorrow, 12 April, will be my first to Point Barrow and the Naval Arctic Research Laboratory. None of my predecessors has visited the Laboratory and Admiral Owen is only the second Chief of Naval Research to inspect a facility now with twenty-two years of history behind it. This fact indicates no lack of interest on the part of our respective offices and I assure you the research programs and other exciting developments at the Laboratory, and within the entire Arctic Basin, are followed with both interest and pride — and usually with approval. It is always gratifying to participate in the celebration of such tangible marks of progress as the opening of new and modern facilities, whatever their function. This is doubly true when the cause is that of research in an area of the world where so much had had to be done with so little. It is earnestly hoped that Parkinsonism does not now set in.

"Greatest pride, of course, must be reserved for the research accomplished; we must not let veneration of things override thought of the results and of the people who both conduct and support research. The record of the Laboratory in all respects is outstanding, and I am mindful of the hundreds of journal publications, research volumes and reports which have emerged from the program, and of the important roles so many have played to the credit of the Navy — and I hope mutually to the scientific community. This symposium has commemorated the Dedication of NARL, displayed many representative achievements, and provided guidance as to the research needs of the future. It is regrettable that not all sciences and fields of engineering which have made significant contributions could be included in the program. Time simply did not permit inclusion of all, but we have heard from a good representative sample of the sciences and the others are not forgotten.

"Co-sponsorship of this symposium by ONR, the University of Alaska and the Arctic Institute of North America is most appropriate. The University has a long and honoured history in arctic and subarctic research and many of its scientists and engineers have made outstanding contributions to Navy programs at NARL and elsewhere. Since 1954, the University has operated NARL for ONR under contract. During that time the Laboratory has made its most rapid and significant growth.

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"On behalf of the Department of the Navy, I wish to express thanks and congratulations for a job of excellence. The Institute provides the advice and guidance of its Board of Governors, Research Committee and its entire membership as needed and has, since 1953, conducted a substantial subcontract program of research for ONR. The Institute, too, has our thanks and a hearty 'well done.'

"I also wish to acknowledge and express gratitude for the fine and helpful relationships which exist between NARL and the Army, Air Force and other government agencies in Alaska. Especially, I wish to thank the Alaskan Air Command which is charged with the responsibility of operating the Base Camp at Barrow. The fine support given by the Air Command, and its civilian contractor, to the Laboratory is appreciated; in a very real measure, it supports the total national research interest, renders the tasks of NARL notably easier and, we may as well admit, results in accomplishments of research at much less direct cost to the Navy. I hope my thanks will be conveyed to the many officers and men at Elmendorf Air Base who give so generously of their time, energy and interest in assisting NARL.

"Now, I should like to turn to what I feel are a few important points to be made relative to the history and growth of NARL. Dr. Reed has given an excellent review of historical facts concerned with the development of the Laboratory. I have no wish to be repetitive or to dwell on history, but a few things should be said. From the beginning of NARL, the ONR policy has been to:

1) Provide facilities at Point Barrow for fundamental research in all appropriate scientific fields related to the arctic environment.

2) Afford facilities within the Laboratory and also facilities as a base for field studies in arctic Alaska.

3) Stimulate and promote basic research in the interest of national security.

"Those simple statements of policy cover a broad field and have served as excellent guidance over the years. They remain as guidelines today. For one reason or another, program emphasis has changed and will continue to do so in the years ahead, but the role of NARL is very likely to remain that of providing working facilities for research ashore and as a base for investigations in the field both at sea and on land.

"The relative weight given to the sea and land programs by the Navy can surely be stated as favouring the sea and this has always been the goal.

"Funding of NARL in FY 69 is slightly less than $1,500,000, the highest in its history and representing a ten-fold increase over the past decade. Never has the Laboratory been sufficiently funded to handle adequately the large number of tasks assigned to it and this is no less true at this time. Yet, noteworthy growth and scientific achievement have resulted even though often with considerable hardship and excessive austerity. While growth has largely benefited the marine sciences, especially the drift station programs, others, including terrestrial research, have not been entirely neglected. Parochial views are frequently expressed in favour of one scientific field or another receiving more thorough support at the expense of others. Such hard decisions have been made on occasion and there will inevitably be others, but characteristic of the ONR policy is the attempt to share resources with all sciences and all federal agencies which sponsor or support them.

"Probably nothing has contributed so much to the growth of arctic research in the United States as the simple existence of a laboratory, which can and does attract users. This growth has been enhanced by the ONR policy of participation in the research of other agencies through the mechanism of the ONR contribution taking the form of non-reimbursable logistics services at NARL. After many years of this practice, which has in effect been a pump-priming effort for the good of all, there are signs of changing times, but I shall come back to the point later.

"It is easy to pick out deficiencies in programs and it must be acknowledged that there are many in arctic research. In a more positive sense, we can cite the many accomplishments of this research, and other attributes of the program, which place the Navy and the Nation in a much more knowledgeable position than it enjoyed 25 years ago. Although I have no intention of reciting long lists of accomplishments, a few highlights will be indicated, some of these having demonstrated pay-off of a nature unforeseen when the research was started and that, of course, is the beauty of basic research.

"Not all of the examples I cite relate to ONR or NARL attainments — other parts of the Navy also are involved in the Arctic. For example, improved sonar techniques developed at the Naval Undersea Warfare Center have enabled the Navy safely to operate nuclear-powered submarines beneath the ice. Such successes are, however, based upon many different kinds of knowledge and much of it is attributable to the basic programs at NARL and elsewhere. I am reminded of the fact that Dr. George MacGinitie, in conducting his marine biological program, was the first to find and partially describe the Barrow Sea Canyon which notches the Continental Shelf off Barrow. This valley system was used by SSN *Nautilus* in 1958 as a route of access to deep water of the Arctic Basin. Caught between the thick over-lying ice and the shallow bottom of the Chukchi Sea, penetration to deep water would have been impossible except for knowledge of the position and configuration of the Sea Canyon. Progress in determination of bathymetry and bottom topography has generally been good within the Basin and enables both improved bottom navigation and hydroacoustic applications.

"Among other Arctic Basin studies which may greatly improve operational capabilities of the Navy are physical, chemical and biological oceanography; details of ocean bottom heat flow and thermal structure of bottom water; acoustic properties and biological, climatic and ice histories as derived from the investigation of sediments; aeromagnetic and gravity surveys; surface circulation and ice drift, and many features of underwater, under-ice acoustics including long range propagation, effects of ocean bottom and ice reflectivity, signal attenuation and transmission loss in ice, ambient noise effects and biological relationships of deep scatter layers.

"Especially significant has been the determination of the arctic radiation balance. Through the research of Dr. Untersteiner and his colleagues, the relationship of heat balance to the annual ice budget is sufficiently known to enable development of a numerical model which permits computation and prediction of ice thickness and temperature for given assumptions of atmospheric and oceanic heat flux. Further refinement of this model will lead to many applications to naval operations. It has been most useful in challenging the belief existing in some quarters that the pack ice may melt out of the Arctic Basin within a few years or decades.

"While on the subject of ice, the accomplishments of Dr. Harold Peyton of the University of Alaska should be mentioned. His studies of basic ice properties and their relationship to engineering strength have many applications to Navy and Coast Guard ship operations and design. Furthermore, his results and expertise have been widely sought and used by the oil industry in the construction of drilling platforms in ice-infested Cook Inlet. I also understand he is kept very busy by the oil interests and the Department of Transportation in their attempts to devise transportation systems for moving oil from the north coast of Alaska. All such applications resulting from Navy-sponsored research are to be applauded.

"Other research with large economic pay-off beneficial to the Navy, other military departments and to the economy, shifts our attention to the land. The extensive investigations of Dr. Robert Black, Dr. Brewer and Dr. Arthur Lachenbruch with reference to perennially frozen ground have been of immeasurable value to rational engineering practices related to the construction of buildings, roads and airstrips. Although I shall not discuss here the large number of important physical and biological programs that have taken place on the North Slope of Alaska, their importance is recognized. We are dealing with large environmental systems which do not stop at shorelines, and the understanding of these, whether atmospheric or terrestrial, is essential. Even the Navy must know much of environments over land, especially for those surfaces bounding the Arctic Basin, as many of its operations also take place ashore.

"It is predictable that current developments on the North Slope of Alaska will result in problems of pollution, and it is certainly known that, at a minimum, activities there desirable though they be are disruptive to the natural physical and biological processes of that landscape. The investigations at present conducted may provide the only record of natural, tundra environmental systems prior to the massive advent of new human intrusion. Such studies no doubt provide the only guidelines for protection of the last great frontier in the northern hemisphere. If an understanding of ecological systems and their tenuous balance effects the preservation and protection of natural systems, as I am sure it does, the Navy, as well as other agencies, will be repaid many times over for NARL's research into these matters.

"It is probable that in the course of time these attributes of our programs may yield the most in furthering the welfare of the United States. I have been told the Navy, too, has contributed its share to disruption of the tundra surface. If this is so, we have the obligation to do our share in investigating the impact of our sins and, learning by experience, to correct the old errors and avoid them in the future. We hope to continue to do our part and encourage others to do the same.

"And there are accomplishments other than those of a purely scientific nature which should be mentioned. Hundreds of people have received their first experience with the arctic environment at NARL and other northern field stations. Many have faithfully returned year after year to extend our knowledge With them resides the principal body of expertise in arctic science, engineering and operations, and upon them the country is largely dependent for any peacetime or other exploitation of the North. The Navy, no longer responsible for icebreaker operations, with no manned bases within the Arctic, and with only rare submarine transits under the ice, lacks any substantial training ground for personnel for arctic duty. Training received in antarctic service is no doubt transferable to northern operations in some degree, but it appears that the civilian cadre of experts is the principal resource available in time of need. It is essential that this training be continued and expanded. It is interesting that the principal Navy toe-hold in the Arctic is a research laboratory. Its record of positive response to large research support problems, efficiency of operation, magnificent safety record and maximum utilization of native manpower resources are worthy of admiration.

"During the Symposium, speakers have individually charted courses for future research in their respective disciplines. All of these are worthy of our attention and support. The course the program of any given agency may take is reasonably, but not always, predictable. Within the Navy which has its own goals and missions, it is only realistic to assume major effort must be given to the oceans. Understanding of the oceans, however, requires knowledge of interactions with the land and atmosphere and, for many compelling reasons, the Navy cannot ignore the ionosphere. This gives us considerable scope for broad and diverse programs. All aspects of dynamic environmental systems must be investigated on a continuing, long-term basis. Full application must be made of automatic, unmanned stations, additional manned stations as well as remote sensing, airborne and satellite systems which can provide required synoptic data.

"Oceanography in general, and probably no less true for the Arctic Ocean specifically, has progressed to the point that research must be based upon experiments designated to answer specific questions. A case in point is concerned with ice behaviour. One accomplishment under the ONR program is a model of ice drift relating the several forces operating on ice. A serious deficiency of the model is the lack of quantitative terms for the internal stress of the ice. Under consideration at this time is a large experiment to measure both the external forces and the resultant behaviour of the ice. Essential to this experiment is an array of three or four pack-ice stations separated by distances of 100 to 150 kilometres, furnished with all necessary equipment for measurement of environmental and ice stress as well as instrumentation for precise navigation, probably by satellite. It is hoped this experiment can be conducted within the next year or so and that several agencies and academic scientists will participate. The results of such a study will not only answer important scientific questions but will greatly improve the accuracy of ice forecasting.

"Other examples of research that are very likely to be initiated or accelerated are: 1) refinement of knowledge of the arctic radiation balance and ice budget in order to evaluate the trend of ice equilibrium thickness; 2) a major effort, probably necessarily international in scope, to determine the magnitude of mass and energy exchange between the Arctic and other oceans; 3) determination of the ratio of ice to open water throughout the ice pack and at all times of the year, such data being badly needed in support of submarine through-the-ice surfacing operations and communications, and for further evaluation of the effect of open water thermal transfer on the annual heat budget; 4) all aspects of under-ice acoustic propagation which will improve numerous applications to naval operational problems; 5) investigations of the basic physics of sea ice and development of techniques for through-the-ice communications.

"The few ideas I have expressed before digression regarding future research, and others mentioned in the course of the Symposium, all involve considerable outlays of money. The magnitude of the job to be done clearly indicates the need for increased funding, but it is well known that competition for R and D funds is very keen and there are many pressing and often conflicting demands.

"The total Navy budget for arctic work of any kind is modest, for basic research even more modest. The latter mostly resides in the ONR Arctic Program, supplemented somewhat by other ONR programs such as Oceanography. Speaking only for the ONR Arctic Program, the total expenditure, exclusive of Military Construction funding, during the 1969 financial year amounts to $2,425,000. Of this amount, approximately $1,440,000 provides for the operation of NARL, including operation of Drift Station T-3, and $985,000 for research contracts and some logistics costs paid directly by ONR to other government agencies. It must be remembered, however, that ONR participation in support of research of other federal agencies is furnished through the University of Alaska budget for NARL. During the past few years, those programs have about equalled in number those funded by ONR contracts and Arctic Institute/ONR subcontracts. It must also be borne in mind, as previously mentioned, that the Alaskan Air Command furnishes the basic camp support at Barrow; this is a real and appreciable contribution to logistics costs. I shall not at this point attempt to predict the future of budgets but I do recognize the very apparent need for additional resources.

"Among the encouraging signs for the future is the modernization of the physical plant at Barrow. The dedication represents a first step, not in expansion, but in modernization and replacement of the old. The second step is already under way as pilings are now being set for the construction of an Aviation Maintenance Facility and a Radio Communication Facility. Erection of these structures will start with the late summer arrival of materials on the annual, barge resupply.

"I should like to mention that communication functions of the Navy, including NARL, will be taken over by the Naval Communications Station, Kodiak, beginning in FY 70 and at Fletcher's Ice Island T-3 in FY 71. The Navy Military Construction submission for FY 71 includes a badly needed Power Plant and Electrical Distribution System for the Barrow Camp and the Second Increment of the Laboratory Building. We shall have to wait to see how these fare with the Congress. Plans are being made for other annual improvements over the next several years and earnest effort is being devoted to the provision of suitable family living quarters. The latter constitutes a difficult problem and no estimate can be given at this time as to our probable success. I have been informed of the desperate need for family quarters and I look forward to getting first-hand information on this.

"There are several lines of evidence, both within and outside the Navy, indicative of widespread interest in arctic research. Certain of these may be taken as holding at least a promise of increased programs although some may represent only realignment of resources and changing goals. A few of these will be cited.

1) At the suggestion of the Chief of Naval Research, I requested both an evaluation of Navy arctic research and the preparation of a long range plan. Dr. Waldo Lyon of the Naval Undersea Warfare Center, San Diego, was assigned this task and I surmise many of you have played some part in the accomplishment of this plan. Dr. Lyon's report has just been received in my Office and awaits critical review and evaluation. It is expected that this report will furnish valuable guidance to future programs and will have broad implications to the research of both academic and Navy in-house laboratory scientists and perhaps NARL as well. I regret that the time is premature for further comment on this report.

2) Last year, the National Science Foundation was given the responsibility of organizing the Interagency Coordinating Committee for Arctic Research. Participation by representatives of all government agencies having arctic research interests and programs provides the means of maintaining an annual inventory of research in progress and its coordination. Other functions will be planned and assumed by the Committee as needs become apparent.

3) The National Science Foundation is planning the initiation of an Arctic Research Program as soon as the funding picture permits. We hope the Foundation will find this possible as early as FY 70. I am sure Dr. Louis Quam who, for many years, gave such good guidance to Navy arctic research and to the development of NARL will enjoy equal success in his new role with NSF. We wish him well!

4) The Committee on Polar Research of the National Academy of Sciences, has in progress an appraisal of the status of arctic research and the development of long range plans for each of the major scientific disciplines. The Glaciological Panel has published its report, including many valuable suggestions with reference to sea ice. All other Panel reports are expected within a few months and it may be fully expected that all will be sources of scholarly opinion and judgement for the guidance of program planners.

5) As a result of the exciting oil developments on the North Slope of Alaska the Department of Transportation has made a statement of policy with respect to transportation. This policy provides for "development of a transportation system in Arctic Alaska requiring public and private investment." Studies are in progress on the means of providing access to Arctic areas and to systems "capable of transporting passengers and both bulk and general cargo" as well as "the feasibility of extending the shipping season so as to permit development of ocean transportation to and from Arctic Alaska." Both government and private investment will provide a great stimulant to additional long range research.

6) The National Council on Marine Resources and Engineering, composed of officers of the Executive Branch, was formed by the President in response to Public Law 89-454, the Marine Resources and Engineering Development Act of 1966. In its annual report of 15 January 1969, the Council included statements as a point of departure in consideration of a National Arctic policy which if adopted will have broad implications with respect to Alaska and the Arctic in terms of scientific, economic, transportation, political and other interests. The report was forwarded to the Congress by the President on 17 January 1969.

7) Public Law 89-454 also directed the President to establish a Commission on

Marine Sciences, Engineering and Resources. The Commission, composed of leaders from industry, universities, laboratories, federal and state governments and others engaged in marine sciences and technology, was charged to recommend an overall plan for an adequate national oceanographic program that will meet present and future national needs. The Commission's final report, made as directed to the President, via the Marine Council, to the Congress, was submitted 9 January 1969. It makes extensive recommendations related to marine sciences, perhaps the most significant being the proposal for organization of a new agency.

"All of my foregoing examples are illustrative of increasing focus on the Arctic and of intense, new and exciting interest on the part of both government and private enterprise. To these may be added the *purely* scientific interest of those who increasingly stimulate and accomplish research. As funding proceeds on a broader national base and with greater assurance of long term continuation, there is even greater need to train the students who will carry the future research burden. In the past, there has been all too limited opportunity to bring graduate students along to fruitful arctic careers in the absence of assured futures in that area. Perhaps we will soon see some alleviation of this problem.

"In any event, there is ample evidence of ferment in the North, and in behalf of the North, and we all know of the wonderful products resulting from that process — by both biological and intellectual avenues. The impact of all developments, real or potential, in terms of the Department of Navy, the ONR Arctic Program and of NARL specifically is uncertain. The future role of the Laboratory is sure to undergo change. The Chief of Naval Research receives much advice on this score and it runs the gamut from large expansion of a valuable Navy asset to its complete abandonment as a Navy research facility. It is unlikely that either of these extreme options is in the offing. Rather I think we can expect modest growth, increased attention to programs of basic research most relevant to the Navy mission, and greater participation of other agencies, including those with their own missions as frames of reference. Perhaps the National Science Foundation can accommodate those areas of investigation unfettered by relation to any mission other than competent research.

"I have alluded several times to the fact that NARL has been operated in the past essentially as a national facility. I repeat that this policy has been effected by the generous participation of ONR in the programs of other federal agencies by furnishing the services of NARL. There are now many signs of erosion of this philosophy in these changing times. Demand has long out-stripped resources, funding is short and any responsible agency must look to its own objectives and how best to meet them. Already there is increasing necessity of reimbursement for the services of NARL and, if the broad nature of research programs so characteristic of the past is to be preserved in the future, broader funding support of those receiving the benefits will be essential. With appropriate arrangements between funding agencies NARL could conceivably become a national laboratory in fact and serve the needs of all. Such mutual participation could do much to speed the growth of facilities, including family housing and other adjuncts to civilized living which would permit longer tenure of personnel and enhance opportunities for more resident scientists and continuing programs. In this connection it has also been proposed that NARL be established as a naval facility and be operated as an in-house laboratory, but this problem has not yet reached a serious decision level. Perhaps a mix of in-house and contract research would also afford a mechanism for improved research.

"There will be many decisions to be made, but no matter what the course of events may be, prospects appear bright for the University of Alaska, the Arctic Institute of North America, the Naval Arctic Research Laboratory, scientists and engineers, and state and federal agencies — perhaps even including the Department of Navy. We shall do our best in the common cause."

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13. ABSTRACT

Interest in northern Alaska and its arctic waters was first shown by the U.S. Navy late in the nineteenth century. However, it was not until 1923 that this interest materialized with the establishment of Naval Petroleum Reserve No. 4. Extensive exploration began there in 1944, and in 1947 the two-year-old Office of Naval Research (ONR) initiated the operation of the Arctic Research Laboratory at the Barrow base camp of NPR 4; twenty-two years later the new Naval Arctic Research Laboratory (NARL) was opened.

The Office of Naval Research had sought the advice of the equally young Arctic Institute of North America (AINA), among others, concerning the proposal to establish the Laboratory. Since that time ONR, NARL, and AINA have been closely associated in numerous projects and programs and, in fact, the Symposium held in connection with the dedication of the new Laboratory in 1969 was co-sponsored by the Institute, ONR and the University of Alaska.

For these reasons it was considered appropriate to publish in Arctic the papers emanating from that Symposium; thus this issue contains seventeen substantial statements giving the major scientific accomplishments in the principal fields of NARL-based research to date, with predictions and recommendations for the next twenty years' studies.

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